Specifying the Graphic Characteristics of Words That Influence Children's Handwriting

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Abstract

Research about the development of the graphomotor side of writing is very scarce. The goal of this study was to gain a better understanding of what constitutes graphic complexity of written material by determining the impact of graphic characteristics on handwriting production. In this end, the pen stroke of cursive handwriting was precisely described through an algorithm of detection of seven graphic characteristics: the number of angles, turn backs, curves in X and Y, pen-ups and modified links. Twenty typically developing children in grade 2 completed a single-word dictation task, composed of 48 items, on a digital writing tablet. All 48 words were regular words, highly frequent for second graders, and varied in terms of their graphic structure. Their handwriting production for each word was assessed in terms of both legibility and speed. A general linear mixed model was run to determine the impact of each graphic characteristic on handwriting performance. In agreement with our hypothesis, the results showed that words have different levels of graphic complexity. The following characteristics, in order of importance, significantly influenced negatively handwriting legibility: modified links, angles, curves, pen-ups and length. Regarding speed, the angles were the only characteristic that made children slow down while handwriting. These findings represent novelty in the field of research on writing. Unlike the usual approaches, it focused on investigating the graphic complexity at the word-level. It offers for the first time a universal classification of the graphic characteristics of words and it enables the quantification of the graphic complexity of words.

Keywords: handwriting; graphic complexity; writing acquisition

Specifying the Graphic Characteristics of Words That Influence Children's Handwriting

Writing occupies a very central role for human communication in everyday activities (Kandel & Perret, 2015; Wicki, Lichtsteiner, Geiger, & Müller, 2015). At school, writing plays a crucial role in academic achievement, and mastering written language is a priority goal for children from the very beginning of primary school (Puranik, Al Otaibia, Sidler, & Greulich, 2014; Wilson & Trainin, 2007). Individual differences are present in children beginning when they first learn to read and to write. Learning to write is very complex in terms of the cognitive processes involved since it requires the acquisition of at least two main components: orthographic abilities to produce accurate spelling and graphomotor abilities to produce handwriting. While the development of both abilities has often been investigated in isolation, very few authors have studied the two components of writing simultaneously (Kandel & Perret, 2015). Little is known about the developmental trajectory of writing. More precisely, the nature of the interactions between the two sides of writing during handwriting acquisition remains to be clarified. Recent studies conducted on typically developing children and children with dyslexia provided findings that support the idea that graphomotor abilities have a significant influence on spelling (Graham, Harris, & Fink, 2000; Jones & Christensen, 1999; Pontart et al., 2013; Van Reybroeck & Hupet, 2009; Wicki et al., 2015). Other studies demonstrated that spelling skills have an impact on handwriting production (Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; Kandel & Perret, 2015; Sumner, Connelly, & Barnett, 2013). However, these studies do not allow a comprehensive understanding of writing development as there is no consensus on the interpretations of their results. One explanation may be that they do not assess handwriting in the same way, frequently using assessments focused on only one aspect of handwriting, such as fluency, speed and/or legibility. Moreover, in those studies, assessments were at a global level, with authors looking at children's handwriting production as a whole. They did not aim to identify the graphic characteristics at the word level that lead to difficulties in writing production, not allowing to get insight into the underlying processes at stake in the development of handwriting. However, this perspective could be essential to further understand the interactions between orthography and graphomotor gestures.

Therefore, the goal of the present study is to specify the graphic structure of words to gain insight into what constitutes graphic complexity to be able to answer the following questions: How can we specify the graphic structure of written material? Are some graphic aspects comprised in words more complex than others to produce? To that end, the present study will establish a classification of the graphic characteristics of words, enabling the determination of the influence of each characteristic on handwriting production. It will, for the first time, provide a universal classification enabling the accurate description of any word's graphic structure. In doing so, our findings will allow insight into the particular aspects of graphomotor gestures that lead to difficulties for children, which is an advancement in the understanding of graphic complexity and children's learning processes. Future research will be able to use this new information to better understand handwriting acquisition, thanks to the precise calculation of graphic complexity. This constitutes a step forward, to be in position to support the way handwriting is taught to children, and to better address difficulties.

The first part of this introduction will outline the gaps found in the literature regarding the question of the interactions between the two sides of writing. The second part will highlight the necessity of developing accurate tools that enable the fine-grained investigation of the graphomotor side of writing, by revealing the lack of consistency in approaches and handwriting assessment methods.

The Study of Both Sides of Writing Production

It is widely accepted that children with dyslexia systematically struggle not only in reading but also in spelling (Snowling, 2000). Moreover, their motor abilities are also suspected to be poorer than those of typically developing children (e.g., the sensorimotor deficit theories of dyslexia, see Savage, 2004). For these reasons, the case of children with dyslexia drew several authors' attention, with their handwriting becoming the object of investigation. Several studies have demonstrated that dyslexic children frequently experience difficulties in graphomotor abilities, leading to slow handwriting (Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008). In this way, some authors showed that dyslexic children performed below their typically developing peers in terms of the quality and size of the texts they produce (Connelly, Campbell, MacLean, & Barnes, 2006) as well as the legibility of handwritten letters (Alamargot et al., 2014; Martlew, 1992). Conversely, authors suggested the alternative interpretation that dyslexic children would not have difficulties in terms of graphomotor abilities as such, but that they would be disadvantaged because of their spelling deficits (Cheng-Lai et al., 2013; Sumner et al., 2013). They argued that the slowness of dyslexic children in writing tasks is the reflection of their difficulty in finding the correct spelling of the words, leading to more pauses. Thus, there is no consensus between authors on how dyslexic children's slowness should be interpreted, and the literature has not yet reached a clear explanation for these handwriting difficulties. Further investigation focused on handwriting production is necessary to better define the difficulties of dyslexic children.

From a developmental perspective, the two components of writing, i.e., spelling and handwriting, are usually referred to as central and peripheral processes within the literature (Planton, Jucla, Roux, & Démonet, 2013). Van Galen (1991) integrated both central and peripheral processes by including those two main abilities within a single model. In this model, higher-level modules, referred to as linguistic and spelling processes (i.e., central processes) are followed by the activation of lower motor components, the peripheral processes. When beginning to learn how to write, children need to recruit most of their resources for the graphomotor gestures. It is a long learning process, with the automation of the motor side of handwriting only occurring in the final years of primary school (Mazeau & Pouhet, 2014) and continuing to progress throughout secondary school (Alves & Limpo, 2015). Through years of writing experience, handwriting production becomes less demanding, and children's movements become more automatic. This progressively releases more resources that can be dedicated to the central processes, including spelling (Pontart et al., 2013). It should also be noted that this motor automation can occur more or less quickly depending on the learning context. The instructional methods in first grade vary from one country to another (e.g., script style in most English-speaking countries, cursive style in France and Belgium), and the constraints are not the same depending on the handwriting style taught. For example, cursive style (i.e., joined letters) has been shown to require more advanced fine-motor abilities compared to script handwriting (Paoletti, 1999). A study conducted by Bara and Morin (2013) revealed that while being more legible than script style, cursive handwriting is the slowest style.

Studies that have investigated the two sides of writing within the same experiment are scarce, and they provide evidence of the interaction between spelling and graphomotor abilities. The two directions of causal relationships have been investigated. On the one hand, the impact from the orthographic side of writing on handwriting performance has been demonstrated, and on the other hand, the influence of children's graphomotor abilities on spelling has been shown. Indeed, research has shown that the orthographic characteristics of words determines the variability in handwriting production. Indeed, Kandel and Perret (2015) have revealed that copying irregular words led to a more dysfluent graphomotor gesture and decreased writing speed compared to regular words. Several authors, giving evidence in favour of the influence of graphomotor abilities on spelling performances, have also demonstrated the opposite relationship. Some have shown that handwriting skills explain the variability in performances in lexical spelling (Pontart et al., 2013) or in text production

(Jones & Christensen, 1999). Van Reybroeck and Hupet (2009) have also demonstrated that when the graphomotor gestures required more resources, children made more spelling mistakes on grammatical agreements. Alves and Limpo (2015) have proved that, during text composition, handwriting fluency contributes to writing speed to a greater extent than spelling skills. An important finding provided evidence that handwriting automation has a positive impact on spelling (Wicki et al., 2015). The authors deduced that handwriting automation allows children to have more working memory resources available for higher processes of writing: orthography. Finally, an intervention study conducted among first graders highlighted the benefits of handwriting training on orthographic abilities (Graham et al., 2000).

To summarise the issue, it is still unclear to what extent handwriting impacts spelling and vice versa. While the orthographic complexity of words is easily manipulated through psycholinguistic variables (e.g., regularity in Kandel & Perret, 2015), no researchers have yet investigated the graphic complexity of words. Therefore, authors have not yet identified the particular aspects of graphic production, at a word-level, that could lead to difficulties for typically developing children and children with dyslexia during writing acquisition. Moreover, the studies mentioned above often analysed the handwriting process as a whole, without tackling the question of the underlying processes implied. One important avenue to gain insight on these gaps may be to adopt a more precise angle of approach in the investigation of the motor side of writing. Furthermore, analysing more precisely the aspects of handwriting execution could help understand with more certainty the different results from experiments conducted on writing development.

Handwriting Assessment

Another part of the uncertainty regarding writing developmental trajectories could be explained by strong differences between the assessment methods used by authors. When taking into consideration the literature regarding the two sides of writing completely, and when comparing the methods employed, a lack of consistency between studies clearly appears. Some authors focused on measuring speed, others only took fluency in consideration, and some chose aesthetic criteria to assess the legibility of handwriting. Moreover, the way researchers have been analysing the same handwriting component is not stable across experiments. A more fine-grained analysis of handwriting dynamics and legibility would provide more evidence regarding writing development.

With regard to measuring speed, Wicki et al. (2015) used the number of letters written during a five-minute copying task to assess children's handwriting speed. In other cases, researchers used the information extracted from digitisers and interactive pens given to children completing handwriting tasks. Pontart et al. (2013) measured two scores: pen movement speed in cm/s, which includes the time spend on a tablet surface; and handwriting duration, which represents the total time to produce a dictated word, including pauses. Those two measures were used to assess the temporal course of handwriting. The same approach is used in a study conducted by Sumner et al. (2013), who calculated execution speed by dividing the distance covered by the pen by the actual writing time spent on a paper. Other researchers focused on analysing the fluency of handwriting as a reflection of the automation of graphomotor gestures. To measure automation, Wicki et al. (2015) looked at the number of inversions of velocity during handwriting, describing the accelerations and decelerations, which indicate dysfluency. In the same vein, Kandel and Perret (2015) have revealed that copying irregular words led to more dysfluent graphomotor gestures, reflected by velocity peaks during handwriting. Others have frequently used the number of alphabet letters correctly produced in one minute as a measure of fluency (Alves & Limpo, 2015; Jones & Christensen, 1999). In those studies, to be considered as correct, a letter had to be legible and in the right order within the alphabet chain. It is worth noting that this last criterion does not reflect graphomotor gesture execution only, but rather the ability to retrieve from memory a correct sequence of letters (Pontart et al, 2013). The notion of legibility usually refers to a situation in which the letter produced is unambiguous (Alves & Limpo, 2015). Outside the context of alphabet-writing task scoring, very few authors have approached the issue of the aesthetics of handwriting at a word or text level. When they do, the criteria used for assessing legibility also differ, since they come from different scales (legibility scale, Lichtsteiner, Geiger, & Wicki (2008) in Wicki et al. (2015); dimensions from the *Evaluation Tool of Children's Handwriting* by Amundson (1995) in Alamargot et al. (2014)).

In their experiment, Kandel and Perret (2015) aimed at investigating the impact of the word level of orthographic complexity on handwriting performance. Children were asked to copy words with various degrees of orthographic regularity, and the authors looked at letter fluency and duration of handwriting for each word correctly spelt. Kandel and Perret (2015) proposed a finer-grained analysis of handwriting by looking inside the word level. Indeed, they took into account the number of strokes comprised in each letter to balance the graphomotor demands of each letter. Thus, they divided the time taken to produce each letter by its number of strokes. That way, Kandel and Perret (2015) adopted an innovative angle of approach by taking into account the differences in graphomotor demands between letters. This demonstrates their interest in the differences between alphabet letters with regard to their graphic structure. This angle of approach can raise questions: how can we specify the graphic structure of written material? Are some graphic aspects more complex than others to produce? Could spelling be influenced by the graphic complexity of handwritten words? Those issues could be particularly relevant, since the cost engendered by the written material has been proven to have an impact on spelling performances. It may be decisive to specify the graphic complexity of words to be able to manipulate the graphic cost of words, as has been done at a task level. For instance, Van Reybroeck and Hupet (2009) compared children's spelling performances regarding two tasks, completion vs. dictation, that varied in terms of graphomotor requirements. In this study, the authors gave evidence that children had better grammatical spelling accuracy in the less demanding task in terms of graphomotor cost. This supports the idea that, at a task-level, graphomotor gesture demands can impact spelling performances. It would be relevant to address this issue at a more precise level, i.e., inside the word level, by investigating what constitutes graphic complexity of words for children, to capture how graphic complexity can impact children's performances in writing tasks. Additionally, this advance in knowledge would make the manipulation of the graphic characteristics of words used for future experiments achievable, as has been done for orthographic difficulty. Indeed, manipulating the orthographic difficulty of tasks, with the use of psycholinguistic variables (e.g., frequency, regularity in Kandel and Perret, (2015)), gives information on the development of spelling acquisition in children. Manipulating the graphic structure of the written material could also modulate the difficulty of the writing tasks and lead to important findings about the development of handwriting.

To date, only very little is known about the development of the graphomotor side of writing. Indeed, while the development of the orthographic side of writing is well-documented, and while spelling assessments are more consistent throughout different studies, investigating the motor side of writing appears to be much more challenging. Specifically, the level of graphic complexity of written material is not appreciated. The present study aims to identify the graphic variables of words that have an impact on handwriting performances, with a fine-grained analysis of the parameters of handwriting. Specifying the graphic cost of each characteristic of the words enables the development of an objective measure to determine the graphic complexity of the written material. This measure will create an algorithm suitable for any word. For this purpose, we quantified the graphic characteristics of words based on the letters composing them according to pen stroke trajectory. A single-word dictation task composed of 48 items was administered to children in second grade. Their handwriting productions were then assessed by several criteria that reflected the dynamics as well as the quality of the graphomotor gestures. The use of those precise criteria allowed a determination of the impact of the graphic characteristics of words on children's handwriting performances. Our hypothesis was that words are not equally demanding in terms of graphomotor abilities, with some being more complex in terms of graphic structure than others. We made the prediction that the graphic characteristics that lead to difficulties will be reflected by a reduction in speed and poorer legibility of handwriting. By opening new methodological possibilities, this study may contribute to disentangling the issues regarding the interactions between the two sides of writing and the case of children with dyslexia.

Method

Participants

Twenty children in second grade (7.42–8.25 years; *M* = 7.75 *SD* = 0.22; 10 boys; no reported developmental or language delays; no speech therapy) were recruited from an ordinary primary school in Belgium's French-speaking region. The children came from a rural school from a middle socio-economic status. The headmaster and the two teachers gave informed consent, as well as all the children's parents. No selection criteria were used at the start of the experiment. However, exclusion criteria were used in the analysis, to ascertain that children met the required level for their age in several oral and written language abilities. Children were eliminated from the final sample if they scored below two standard deviations for their age in any of the six control tasks described hereinafter:

Only one child was excluded from the final sample (*N* = 19) because he demonstrated performances below two standard deviations in spelling and reading abilities as well as in non-verbal ability.

Materials

We selected 48 words to be written on tablet in a dictation task to analyse a diverse set of words' graphic characteristics to evaluate the graphic complexity of the words.
Since the graphic structure of words had not yet been investigated, we first wanted to establish a list of the graphic characteristics comprised in handwritten words. To do so, four steps were completed. First, we developed algorithms to determine ways of detecting the graphic characteristics of handwriting (step 1). Second, we implemented the mathematic formula at the letter level, that is, each letter separately (step 2). Third, we applied the same process at a word level, allowing the establishment of the graphic characteristics of words (step 3). The last step was to select the words to be used as stimuli during the dictation task and to gather all the information concerning the graphic characteristics of those target words (step 4).

Detection of graphic characteristics on digital tablets (step 1). The aim of the first step was to allow the automatic detection of the graphic characteristics of handwriting. To that end, we generated algorithms to be applied on handwriting produced on digital tablets. The use of the tablets provided information concerning three major aspects of handwriting: (i) *the arc length of the productions*, the total arc length of the pencil stroke in centimetres; (ii) *the pressure of the pen on paper,* information on the variations in pressure was used to detect the moments spent in the air while writing. Some letters require lifting the pen up to be correctly handwritten. This graphic characteristic is referred to as *pen-ups* and is defined by a region where the pressure equals zero; (iii) *the pencil stroke trajectory*, the pencil stroke trajectory was tracked to identify different types of changes in trajectory. The changes in pencil stroke trajectory could be either curvy or, conversely, abrupt. The curvature of pencil strokes occurred on two axes, vertical (Y) or horizontal (X). Therefore, a distinction was made for *Y-curves* and *X-curves*. Concerning the abrupt changes in trajectory, a distinction was made between abrupt changes in terms of the presence of either an *angle* or a *turn-back*.

To sum up, six graphic characteristics of handwriting were established, with the following terminology: length, pen-ups, Y-curves, X-curves, angles and turn-backs. Algorithms of detection were developed to allow the automatic detection of these graphic elements within handwriting. Let **x(t)**, **y(t)** be two continuous functions representing the coordinates of handwriting production at any time **t**, the word's arc length can be expressed as:

$$l = \int_{t=0}^{t=\tau} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2}\, dt$$

Furthermore, the curvature of the handwriting at a time **t** can be expressed as:

$$k(t) = \frac{\left|\frac{dx}{dt} * \frac{d^2y}{dt^2} - \frac{d^2x}{dt^2} * \frac{dy}{dt}\right|}{\left(\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2\right)^{3/2}}$$

The angles and turn-backs can then be defined as regions of high curvature. One curve is counted each time **x(t)** or **y(t)** reaches an extremum (minimum or maximum). A tablet recording provides access to discrete samples of **x(t)** and **y(t)**. Therefore, we used finite difference methods for differentiation and Riemann sums for integration. Figure 1 shows how these equations can be used to detect angles and turn-backs, which can be defined as regions of high curvature. Finite difference methods were used to compute the curvature in each recorded point, and a threshold of 0.10 was applied. All points beyond that threshold are potential angles and turn-backs (cf. Figure 1, shown in red). The algorithm of detection was applied to a child's handwriting, who handwrote the 26 letters of the alphabet (cf. the alphabet task, p18) at two different times. The correlations between the detections of the characteristics in the two productions were all significant,: for pen-ups, $r = .89$ ($p < 0.001$); for the detection of the angles, $r = .75$ ($p < 0.001$); for the curves on Y-axis, $r = .71$ ($p < 0.001$); and for the curves on the X-axis, $r = .50$ ($p < 0.05$). It is worth noting that children's handwriting variability led to different detection patterns for some letters, which is due to the intra-individual variability of handwriting.

Letter level (step 2). The second step was to reach a classification that would allow us to easily identify any word's graphic structure by knowing precisely the elements it contains. To do so, we first started at the letter level. All the letters of the alphabet were written separately on a tablet, enabling us to characterise each letter according to its pencil stroke. As demonstrated by the correlations presented in the previous sub-section, variabilities in handwriting within and between individuals makes the development of robust detection algorithms extremely difficult. To alleviate this, we chose a character font as a reference, identical to the one used by teachers throughout the French-speaking community of Belgium (cf. Figure 2). We ensured that it corresponded to the standards required for children in primary school. We then ended up with information concerning the graphic characteristics presented in each alphabet letter. Figure 2 gives a visualisation of the variables for every letter of the alphabet. A dot appeared when a change in trajectory was detected or when an important variation of pressure occurred.

Word level (step 3). The next step was to adjust our classification for the word level. Since a word is a succession of letters, simply summing the characteristics of each letter composing a word would give an approximate view of the word level. However, the typology used in the Belgian primary schools is a cursive one, which implies joining the letters together by adding links between the letters when writing a word. Therefore, the graphic structure of a word cannot be reduced to the sum of the characteristics of the letters composing the word. One specific case, the *modified links,* required particular attention. This refers to a situation where the link between two letters engenders a modification of the way letters are usually written. For example, when the letter *r* follows the letter *b*, the production of *r* has to be adapted, starting at a different height than usual (cf. *branche* in Figure 1). Since we believed modified links could be source of handwriting difficulty for children, several successions of letters were handwritten on a tablet, making sure they covered all types of existing pairs of letters. Our algorithms were applied to these productions recorded on a tablet, and the results were adjusted for the modified links. The number of angles, turn-backs, curves in X and Y, pen-ups and modified links of any letter or letter pair were thus available, which enabled us to compute the variables for a complete lexicon, containing 135,000 French words (Lexique 3.81; New, Pallier, Ferrand, & Matos, 2001) by summing over the letter pairs contained in each word. Thus, for each word, seven graphic characteristics were taken into account: the word's length, as well as the number of pen-ups, angles, turn-backs, Y-curves and X-curves, and modified links. Figure 3 illustrates the seven graphic characteristics, with each colour dot representing the presence of a graphic characteristic.

Selection of the stimuli (step 4). Since the aim was to focus on handwriting execution, only words supposed to be mastered in second grade were selected to avoid spelling difficulties (success rates above 85%, *M* = 94.83; *SD* = 3.9 in EOLE [lexical spelling acquisition scale]; Pothier & Pothier, 2003). This precaution allowed us to expect a large majority of the words to be handwritten with the right orthography. By maximising the chances of having similar spelling productions between children, we ensured that the majority of the handwriting production would be similar, hence, comparable. Therefore, words selected were either strongly regular (e.g., *mouton* [sheep]), or highly frequent (e.g., *deux* [two]) or both (e.g., *livre* [book]). To ensure equal testing conditions, the 48 words were recorded using a voice recorder. The items were then arranged using the software Psychopy, making sure children would all hear the words pronounced the same way, in the exact same order.

Once the 48 target words were selected, all the information concerning their seven graphic characteristics were gathered. One last transformation was operated on those seven variables, because word length could impact the handwriting of children. Indeed, the longer the word is, the more it costs in terms of graphomotor resources, with a long word being inherently more likely to be the source of handwriting difficulties than a short word, since it gives more room for errors. By having items that varied in terms of length, the risk would be to wrongly attribute aesthetic errors made by children to the graphic characteristics of the words, whereas it would in reality be related to word length. To avoid this kind of misinterpretation, we used a standardised value for our variables instead of a raw value, which was obtained by dividing the value of each characteristic by the word's arc length, measured in centimetres. Therefore, the graphic variables were weighted depending on the item's length. For instance, the word *branche*, which contained 3 angles and 7 curves in the X axis (cf. Figure 3), had a length of 12.78 cm. The values for the two graphic characteristics mentioned above became 0.23 (3/12.78) for the angles and 0.55 (7/12.78) for the X-curves. Table 1 summarises the seven graphic characteristics calculated for the words selected for the experimental task ($N = 48$).

Measures

Table 2 provides details on our sample's characteristics in control and experimental measures.

Receptive vocabulary. Vocabulary was assessed with a designation task of one of four pictures (ELO, oral language assessment; Khomsi, 2001). This test was composed of 20 items, leading to a maximum score of 20. This is a standardised test, allowing children from our sample to be compared to the French norms for 2nd grade.

Non-verbal reasoning ability. Non-verbal reasoning ability was assessed through the matrices subtest of the WISC-IV (Wechsler, 2005). Children were required to select the best of five response choices, corresponding to the adequate missing piece to fill the matrix. The items were ranked by increasing order of difficulty. Therefore, the experimenter had to stop the task after four consecutive mistakes. The test was composed of 35 incomplete matrices, and the total number of correct responses was calculated. Matrices is a standardised test, and the test norms are available for different age groups, from six to 16-year-olds. For this subtest, the reported internal consistency coefficient is .86.

Word reading. Reading ability was assessed with a single-word reading test administered to the children (LUM, [One-minute reading]; Khomsi, 1999), which consisted of reading the maximum number of the words in one minute. The list consisted 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 quality in copying task. Participants' handwriting was assessed with a text copying task from a standardised test, in a limited time of five minutes (BHK, [Concise evaluation scale for children handwriting]; Charles, Soppelsa, & Albaret, 2004). The quality of handwriting was assessed based on 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 graphical error lead to attributing 1 point. Therefore, low scores referred to good handwriting quality, whereas high scores reflected poor handwriting quality. BHK is a standardised test, allowing the comparison of participants' performances to their school level norms for both speed and quality. The task has a very high reported interrater reliability (r = .90), and the internal reliability within the current sample is .78.

Handwriting speed in copying task. The number of letters correctly copied in the BHK test was scored as a measure of handwriting speed.

Syllable and word-spelling accuracy. Spelling ability was assessed with a dictation task including both syllables and words (BELO [Test battery for reading and spelling assessment]; Pech-Georgel & George, 2006). Spelling those items required both phonological and lexical orthographic abilities, since it consisted of regular words and words with complex phoneme-grapheme correspondences. The test included 10 syllables and 15 words, leading to a maximum score of 25 for the whole task. Children's scores were compared to the norms for 2nd grade on both syllable-spelling and word-spelling. Reliability analyses returned a coefficient (Cronbach's alpha) of .81 in the current sample.

Alphabet writing. Participants were asked to write down the 26 letters of the alphabet, in cursive lowercase, as quickly as possible in one minute. To be considered correct, a letter had to be legible and produced in the right order within the 60-second time constraint. One point was attributed for each correct letter, leading to a maximum score of 26. This measure is not a standardised test, but it shows high reliability and validity properties (Barnett, Henderson, Scheib & Schultz, 2009).

Spelling accuracy in experimental dictation task. Children were given one point for each word correctly spelled, leading to a maximum score of 48 for the task. The internal reliability in the current sample given by Cronbach's alpha is .81.

Handwriting quality in experimental dictation task. Scoring of the experimental task was inspired from the BHK scale (Charles et al., 2004). Five aesthetic criteria were taken into consideration for handwriting quality. They all refer to a type of graphical error. The words were assessed in a binary way, with a score of 1 attributed in cases 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, resulting in 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) poor letter alignment within the word, when horizontality of the handwriting is violated (cf. Table 3). The examiner was given detailed guidelines to assess 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 handwritten word. By summing the total number of graphical errors per word and dividing it by the number of handwritten words, we calculated an average score for each child.

Handwriting speed in experimental dictation task. The time to produce each word was directly extracted from the tablets, measured in milliseconds, giving a score of handwriting speed. The recording started at the very beginning of each word's pen stroke and ended at the very end of the word, including the pauses inside the words and in air phases (i.e., pen lifts).

Procedure

The whole experimental phase occurred in an empty classroom at school and was carried out by the same experimenter within a short time period (three weeks). The control tasks were individually administered in a session lasting approximately 30 minutes, except for the standardised spelling task, which was administered to all the children at once, inside their classroom. The experimental task with tablets occurred in groups of four children, lasted approximately 30 minutes per session, and were conducted by the experimenter and an engineer. The children were simply asked to write down the words they heard, at their usual speed. The experimenter put emphasis on 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 it down as they think best. They were 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. Children were not informed about the focus on handwriting quality. Each child was given a digital tablet and a digital pen (Wacom Intuos Pro Medium and Wacom Inking Pen). The tablet size was 380 x 251 x 12 mm, with an active area of 224 x 140 mm. To have enough space to write down the 48 words, three testing A4 sheets were provided for each child. They were attached to the top of the tablet with tape. Therefore, the testing conditions were close to how they usually write since children had to write on white paper with an inking pen. To make sure children would write within the active zone, the zone was clearly marked out by a frame drawn on each sheet. Additionally, to guide the children throughout the task and to make sure they would write in the correct space, dashes followed by each word's determinant (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 determinant. Their productions were recorded in real time, with a sample frequency of 7/8 ms.

Data Analysis

Statistical analyses were run with SPSS 24. We first conducted preliminary analyses to examine if the data met the normality assumption of parametric procedures. The degree of skewness and kurtosis revealed no distributional problems (all measures $Sk < |2|$ and $Ku < |7|$). A generalised linear mixed model (GLMM) was used, with participants entered as a random factor and the characteristics of the words as fixed effects. For the fixed effects, we used the standardised variables: the raw number of graphic characteristics contained within each word divided by its length. Only words correctly spelt by children were taken into consideration for the handwriting assessment. The influence of the seven graphic characteristics of the items was examined for each handwriting variable separately. Therefore, the GLMM was run six times, once for each dependent variable. There were large individual differences in performances in the single-word dictation task within the present sample, with an ICC of .58 for handwriting speed, suggesting that 58% of the total variability in speed lies between participants. The GLMM analyses offer the benefits of accounting for both the variability induced by participants and that induced by the items within the same analysis.

Results

Correlations Between the Experimental Word-Dictation Task Results and Skills Associated with Word-Writing

Correlation analyses were carried out to show the associations between participants' performances in the different control tasks and the experimental task. Pearson's correlation coefficients are presented in Table 4.

Spelling accuracy. Spelling accuracy in the experimental word-dictation task was significantly positively correlated with non-verbal reasoning score, word-reading in one minute, number of letters produced in the five-minute copying task (BHK), word-spelling accuracy score in the standardised test (BELO), and the number of letters correctly written during the one-minute alphabet task.

Handwriting quality and handwriting speed. The average number of graphical errors per word in the experimental task was significantly related to the average handwriting speed per word. The positive relationship demonstrated that the faster the children wrote, the more negatively impacted their handwriting quality was since they made more aesthetic errors. Quality and speed of handwriting in the experimental task did not correlate to any of the control measures.

Proportion of Types of Aesthetic Errors

Children successfully wrote 80.81% of the words dictated to them (n = 737). The presence of five aesthetic errors affecting handwriting quality was systematically noted for each word. Their occurrence in children's productions turned out to be highly variable. As illustrated in Figure 4, the most commonly made mistake was poor alignment of the letters (M = 0.76; SD = 0.11). Then, abnormal variations in the size of the letters within a word (M = 0.45; SD = 0.14) and distortion of letters (M = 0.34; SD = 0.14) were also quite frequent among the children's productions. Finally, errors in terms of height of letters and corrections of handwriting were very uncommon mistakes, each respectively only affecting 8% (*M* = 0.08; *SD* = 0.06) and 6% of the words (*M* = 0.06; *SD* = 0.05).

Impact of The Graphic Characteristics on Handwriting Speed and Quality

Results are presented in Table 5, with the coefficient between each graphic characteristic and each handwriting variable reported, as well as the associated p-value. The importance of the relationship between the two variables is indicated through the value of its coefficient. The seven lines refer to the graphic characteristics of the words (independent variables, fixed effects), and the six handwriting variables are represented in columns (dependent variables). Only the significant effects are described in the text.

Turn-backs. The presence of turn-backs did not lead to any significant results for any of the dependent variables.

Angles. The speed of handwriting production was slightly negatively influenced by the presence of angles within a word, $F(1, 729) = 21.73$, $p < 0.001$. In other words, the more the words comprised angles, the slower children were to handwrite them. The angles led to significantly more aesthetic errors of two types with higher coefficient values (> 2): abnormal variations in the size of the letters within a word, $F(1, 729) = 8.09$, $p < 0.01$; and abnormal relative height between letters, $F(1, 729) = 6.74$, $p < 0.05$.

X-curves. The curves in the X axis had no significant impact on five of the six dependent variables but seemed to have a minor facilitating impact on one handwriting variable, the respective size of the letters, $F(1, 729) = 4.54$, $p < 0.05$.

Y-curves. Conversely, the curves in Y seem to lead to more difficulties, since they were positively related to errors in letter size, $F(1, 729) = 12.97$, $p < 0.001$, and poor alignment, $F(1, 729) = 13.81$, $p < 0.001$.

Modified links. The modification of a link between two letters was most related to handwriting difficulties, significantly affecting four out of the five aesthetic criteria, with the largest size effects (all coefficients > 4). The analyses revealed a positive relationship between the presence of modified links and production of distortions of letters, $F(1, 729) = 4.4$, $p < 0.05$, abnormal size of letters, $F(1, 729) = 15.57$, $p < 0.001$, erroneous relative height, $F(1, 729) = 9.06$, $p < 0{,}005$, and poor alignment of handwriting, $F(1, 729) = 4.76$, $p < 0.05$.

Pen-ups. Regarding the necessity to lift the pen up during handwriting production of a word, our results showed that it was significantly related to the appearance of abnormal variations in the size of letters, $F(1, 729) = 4.22$, $p < 0.05$, and difficulties in terms of handwriting alignment, $F(1, 729) = 4.15$, $p < 0.05$.

Length. The word length was positively related to the appearance of the five types of aesthetic errors, but with very low coefficients (all coefficients < 1). Word length was positively related to the presence of distortions, $F(1, 729) = 16.37$, p < 0.001, abnormal size, $F(1, 729) = 20.19$, $p < 0.001$, abnormal height of letters, $F(1, 729) = 13.64$, $p < 0.001$, graphic corrections, $F(1, 729) = 12.37$, $p < 0.001$, and lack of alignment, $F(1, 729) = 19.27$, $p < 0.001$.

In conclusion, when looking at the strength of the coefficients, we noticed that the two graphic characteristics responsible for the most handwriting difficulties were the modified link between two letters and the angles contained within words. The modification of links between two letters was the characteristic with the biggest impact on handwriting performance, both in terms of types of aesthetic mistakes and in terms of the importance of the coefficients. Moreover, it should be noted that the angles are the only characteristic that had a significant impact on handwriting speed, in addition to their influence on legibility.

Discussion

This study aimed to implement a fine-grained method to allow the specification of the graphic characteristics of written material. This falls within the context of the unclear results found in the literature regarding the issue of the interactions between the two sides of writing, graphomotor gestures and spelling. We considered that some of the uncertainties found in that field, as well as the very low number of studies focused on handwriting, may be due to the lack of fine-grained methods available to investigate handwriting. The goal of this study was to gain a better understanding of what constitutes the graphic complexity of written material. More precisely, the aim was to reach a classification of the graphic variables contained in words and to determine their impact on handwriting production, allowing us to identify what constitutes graphic complexity for children. To do so, children were assessed on a single-word dictation task on a digital tablet. They were also evaluated on several written language related abilities (e.g., word-reading, syllable-spelling, short text copying). Correlations between children's performances in the different measures showed that spelling accuracy in the word-dictation task was positively correlated to word-reading, non-verbal reasoning, and handwriting speed in the copying-task as well as the alphabet task. Interestingly, performances in the alphabet task correlated to all spelling measures but not to handwriting quality and speed in the word-dictation task. This is surprising, since the alphabet task is often used as a measure of handwriting (Alves & Limpo, 2015; Jones & Christensen, 1999; Sumner et al., 2013). However, this result is congruent with Pontart et al. (2013), who used the alphabet task as a measure of orthographic ability, whereas graphomotor skills were assessed through a name-writing task. Surprisingly, handwriting quality score in the standardised copying task was not correlated with handwriting quality score in the word-dictation task. This can be explained by the fact that the two tasks involved different cognitive processes. Copying mostly requires the peripheral processes of writing, while dictation task is demanding in terms of central processes of writing. Thus, at school, handwriting is often taught through copying (Maldarelli, Kahrs, Hunt & Lockman, 2015), while spelling is assessed through dictation. In addition to being a lot more demanding in terms of central processes, the word-dictation task was composed of 48 words and the standardised copying task (BHK) was only composed of 19 short words. Therefore, the copying-task was a lot shorter and less demanding in terms of orthographic abilities than the dictation task, which could explain why the two tasks are not correlated for handwriting quality.

Regarding our main question, our results showed that words have different levels of graphic complexity. In agreement with our hypothesis, several graphic characteristics significantly influenced the quality and speed of handwriting, some to a higher extent than others. The graphic characteristics contained in words led to different kinds of graphic difficulties, in terms of both legibility and speed, in grade 2 children's handwriting production. These findings represent novelty in the field of research on writing, since, unlike the usual approaches, this study focused on the word level. The following characteristics, in order of importance, significantly negatively influenced handwriting legibility: modified links, angles, curves, pen-ups and length. Regarding speed, the angles were the only characteristic that made children slow down while handwriting.

More precisely, our data indicated that the modified link (e.g., "br" in *branche*) between two letters was the variable that led to the most handwriting difficulties, causing aesthetic distortions, incorrect size and relative height of letters, as well as poor alignment. The modified link is a graphic characteristic specific to cursive handwriting, because it arises from the necessity to join the letters together. In a way, our findings support the point of view of Paoletti (1999), who defended the idea that cursive style is more demanding than manuscript style in terms of fine motor coordination. One explanation for this high level of difficulty compared to the other word characteristics could be that children are taught at school to handwrite the letters of the alphabet in an invariant way, with the shape of the letters expected to be unchanging. They have in memory a template for each letter (Bara & Morin, 2013). When children have to change the way they learned how to produce a letter because they have to join the letters together, they have to cope with an unusual segment, which could be logically less automatised than the most frequent situation, i.e., their template letters.

Our data also demonstrated that the angles caused significant handwriting difficulties, leading to more mistakes in terms of the size of letters as well as their relative height, along with a significant decrease of speed. This large impact on handwriting could reveal that the angles are a characteristic that takes longer to be mastered by children. In terms of the underlying processes of handwriting, one interpretation is that the abrupt changes of pen-stroke trajectory induced by the angles could be more demanding in terms of graphomotor gestures. The fact that the angles are related to decreases in handwriting speed provides evidence in that direction. Indeed, producing the angles implies a rupture of the graphomotor gesture. This leads to more difficulties than curvy segments, which are continuous and, therefore, do not necessitate such precise control in terms of graphomotor abilities. This suggests that abrupt changes in direction require more resources in terms of gesture planning and production than curves do. A study conducted by Thomassen and Van Galen (1992) also gave evidence for this interpretation. Indeed, they stipulated that letters that induced sudden trajectory changes were the most complex regarding motor action.

Curves on the Y-axis also led to handwriting difficulties, causing non-respective size of the letters within words and poor alignment, but to a lesser extent than the angles. This finding is also in agreement with the previous study by Thomassen and Van Galen (1992), who suggested that the most sudden curvature changes are more difficult to produce than continuous trajectories. The curves on the X-axis even showed a slight facilitating effect on handwriting, positively influencing the respect of the size of the letters. This could suggest that the X-curves are the graphic characteristic the most easily mastered by young children.

The necessity to lift the pen up led to two aesthetic abnormalities as well, which were non-respective size of letters and poor word alignment. However, this negative influence from pen lifts contradicts what can be found in the literature. Indeed, some authors support the idea that lifting the pen up could have a facilitating impact on handwriting, because it gives more time for children to plan their next movement (Meulenbroek & Van Galen, 1986). However, this finding did not arise from the same context as in our study, instead coming from the analysis of manuscript style, which requires lifting the pen between every letter since they are not joined. Hence, lifting the pen up in the context of our study, i.e., cursive style, was much more unusual than in manuscript contexts, which could explain why it led to difficulties for children in our sample. An interpretation of our finding could be that lifting the pen up in a cursive context induces a break within the handwriting production, which could be more demanding of graphomotor abilities.

Finally, even if the size effects are very low, the word length significantly contributed to make children produce the following aesthetic mistakes: distortions, non-respect of the size and relative height of letters, graphical corrections and poor alignment. This finding strengthens the fact that the standardisation performed on the graphic variables, which consisted of dividing the graphic characteristics contained in words by the word length in centimetres, was an essential precaution. By doing so, we avoided possible biases of interpretation since we made sure that our observations would reflect not only the impact of the item length but also the graphic complexity.

Lastly, the turn-backs are the only graphic characteristic that did not show any significant effect on any of the six dependent variables. This graphic characteristic did not influence children's handwriting in Grade 2.

Our study fulfilled its main purpose, which was to allow the quantification of the graphic complexity of words. This constitutes a key implication for research. By using the significant coefficients derived from our analyses, it is now possible to generate an equation representing the graphic complexity of any given written material. Moreover, the steps followed to reach our objective provide new information about the variables that constitute written words. The progression we followed led to a new classification useful in specifying the characteristics of words. The seven graphic variables used in our method accurately define the pen stroke trajectory, which reflects graphomotor execution. Using these variables is a fine-grained angle of approach, and they could be used in future research to accurately describe the graphic structure of any written material (e.g., script handwriting, upper case letters). Thus, the method we presented is universal. Our findings have clear implications for research ahead, giving new methodological possibilities for the study of writing acquisition among children. For the very first time, there is the possibility of manipulating the graphic complexity, at the word level, of the material used in experiments. The comparison of performances in writing words that differ in terms of graphic complexity opens new perspectives to clarify the issue of interactions between the two sides of writing. Indeed, it allows investigations of the impact of graphic complexity on spelling.

Our findings can also contribute to designing experiments to better understand cases of children with dyslexia, by examining if such children are more impacted by graphic complexity due to a potential graphomotor deficit, as suggested by the sensori-motor theories of dyslexia (Savage, 2004). These findings open up new possibilities in studying the writing acquisition of children with dyslexia, because they suggest new approaches to compare dyslexic children to their typically developing peers. Regarding the question of speed, we observed among typically developing second graders that one particular graphic characteristic, the angles, led to a reduction in speed. As presented in our introduction to this article, some studies conducted among dyslexic children have noted slowness in handwriting execution (Cheng-Lai et al., 2013; Sumner et al., 2013), but authors have not reached a clear interpretation of these difficulties. One interpretation by Sumner et al. (2013) stipulates that the slowness of dyslexic children is due to spelling deficits. The graphic characteristics classification we developed could play a crucial part in confirming or infirming this interpretation. This system would allow the manipulation of graphic complexity in future experiments, leading to investigations of how dyslexic children's handwriting speed is influenced by graphic characteristics. Regarding the question of the legibility and aesthetics of handwriting, we demonstrated that the angles and the modified links are the most complex graphic aspects to handwrite, leading to aesthetic errors in children with typical development. The studies that tended to demonstrate that children with dyslexia have less legible handwriting (e.g., Alamargot et al., 2014) assessed handwriting performances without taking into consideration the graphic complexity of the words and letters used. Here, again, it would be critical to investigate how children with dyslexia are impacted by the graphic complexity of words in terms of handwriting legibility, with reference to our knowledge about their typically developing peers.

From a practical and educational perspective, our findings shed light on the graphic aspects at the root of handwriting difficulties. Indeed, even though children were at the end of second grade, they still committed a large number of aesthetic errors. This emphasises the fact that acquiring handwriting is a long process, with automation of the motor side of writing only reached in the final years of primary schooling (Mazeau & Pouhet, 2014). Therefore, this is one argument in favour of the idea that learning to handwrite should not be limited to the first year of primary school and should still be the object of explicit teaching and training throughout primary school. Our findings provide relevant knowledge for teachers, giving them information about the graphic aspects they should insist on to help children with the challenging parts of handwriting acquisition.

One limitation to our findings can be found in the fact that they are not directly generalisable to contexts outside of countries that use cursive writing styles. Indeed, the handwriting style taught at school is not universal. There are two main styles taught at school, cursive and manuscript handwriting styles (Bara & Morin, 2013). For instance, the complexity engendered by the presence of modified links due to the necessity of joining letters in cursive script is not relevant for countries where children learn to write in manuscript (e.g., in most English-speaking countries). Likewise, the number of changes in direction, abrupt and curvy, within in each letter differs slightly according to the handwriting style. However, the method used to create and implement the algorithms in this study can be replicated, by following the four steps described in the Method section, to reach classifications that are accurate for any specific handwriting style. Another limitation lies in the age of the children who participated in our experiment. Indeed, children all came from the same grade, meaning that the coefficients we found may not be representative of cases of younger and older children. We cannot be assured that handwriting difficulties remain stable through the years. Some difficulties that are preponderant in grade 2 may not be as important in the later stages of writing acquisition. The same experiment should be expanded to other grades in primary school, allowing us to determine the influence of the graphic characteristics of written material from a developmental perspective. That way, we could obtain a specification of the graphic complexity of words faithful to each school grade, if relevant. Finally, we wanted to have a large number of stimuli to conduct statistical analyses. However, some words may have been too difficult in terms of spelling for some children, since almost 20% of the words were misspelled. This result occurred even after having taken several precautions in the selection of the items. Indeed, only highly frequent words selected from Lexique 3.81 (New et al., 2001), with consistent orthography and high success rates, above 85%, for grade 2 pupils (EOLE [lexical spelling acquisition scale]; Pothier & Pothier, 2003) were selected for the dictation task. Even if we only considered the correctly spelled words, this precaution does not entirely ensure that our measure of speed is only the reflection of the motor production of writing. It could also possibly be influenced to a certain extent by the orthographic cost of the dictation task, with some children slowing down to think about correct spelling during handwriting. Further studies should also carefully select the words and only use items adapted to children's school level to avoid this possible bias from the influence of the orthographic aspect by making sure all words were actually mastered by children.

Conclusion

Overall, the present study leads to a better understanding of what constitutes the graphic complexity of written material. Thanks to the fine-grained analysis of the graphic characteristics contained in words, this study offers for the first time a universal classification allowing the specification of any written material by quantifying the presence of seven graphic variables. The findings give rise to new possibilities for the field of writing research, allowing new approaches for the investigation of writing acquisition. Future research will be in position to determine to what extent the graphic complexity and orthographic complexity of words interact and to investigate whether children with dyslexia may react more strongly to graphic complexity than their typically developing peers. Our findings also have practical implications by opening new potential pedagogical guidelines for teaching handwriting at school.

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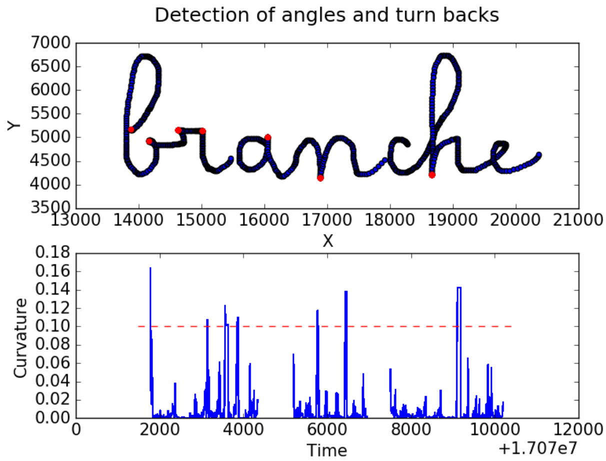


Figure 1. Illustration of the detection of angles and turn-backs.

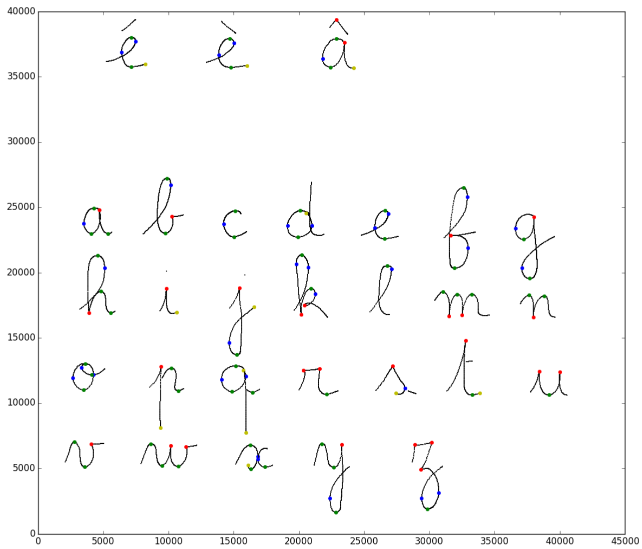


Figure 2. Detection of the graphic characteristics of handwriting of alphabet letters.

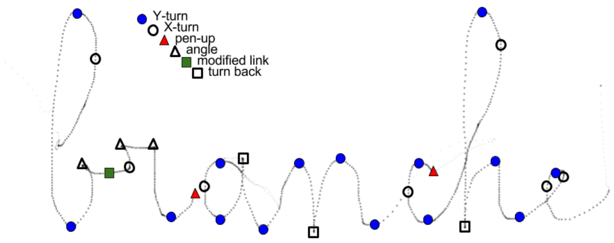


Figure 3. Visualisation of six graphic characteristics for the word *branche* [branch]. The last characteristic is the item's pen-stroke length, measured in cm (here, item length = 12.78 cm).

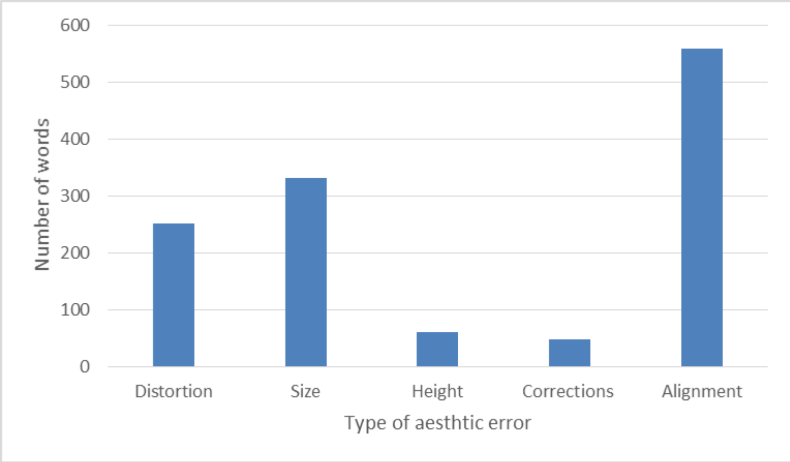


Figure 4. Distribution of the total aesthetic errors made by children.

Table 1

Descriptive Statistics for the Seven Graphic Characteristics of the Stimuli, Based on Raw Values and Standardised Values

Raw	Length (L)	Angles	Turn backs	Y-Curves	X-Curves	Pen-ups	Mod. links
Mean	8.97	1.6	3.21	10.9	5.08	1.02	0.21
SD	1.97	1.43	1.92	2.91	2.3	0.85	0.41
Standardised	Length (L)	Angles/L	Turn backs/L	Y-Curves/L	X-Curves/L	Pen-ups/L	Mod. links/L
Mean	8.97	0.18	0.35	1.21	0.57	0.12	0.21
SD	1.97	0.16	0.19	1.88	0.25	0.11	0.41

Table 2

Participant Performances on Control and Experimental Measures

Measure	Mean	Standard Deviation
Vocabulary score (/20)	16.47	1.90
Nonverbal reasoning score (/35)	18.05	4.46
Word reading in one-minute accuracy score	40.58	15.33
Copying task: handwriting quality (number of graphical errors)	14.79	6.10
Copying task: handwriting speed (number of letters copied)	147.16	40.38
Syllable-spelling accuracy score (/10)	9.79	0.52
Word-spelling accuracy score (/15)	10.16	2.66
Alphabet task score (/26)	19.26	4.61
Experimental task: spelling accuracy (/48)	38.39	6.31
Experimental task: handwriting quality (number of graphical errors	1.69	1.05
per word)	1.68	0.68
Experimental task: speed of handwriting		

Table 3

Recap and Illustration of the Six Assessment Criteria

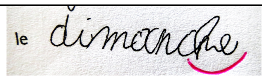
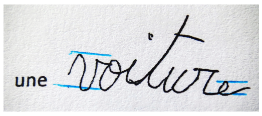
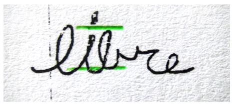
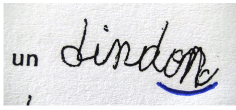
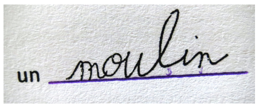
Handwriting variables		Examples
Aesthetic criteria	Distortion	
	Letter size	
	Relative height	
	Correction	
	Alignment	
Speed		Extracted from the tablet

Table 4

Measure	1	2	3	4	5	6	7	8	9	10
1. Vocabulary (ELO)	–									
2. Non-verbal reasoning (WISC)	-.338	–								
3. Word-reading accuracy (LUM)	-.111	.364	–							
4. Copying task: handwriting quality (BHK)[a]	-.187	-.155	-.421	–						
5. Copying task: handwriting speed (BHK)	-.224	.452	.565*	-.307	–					
6. Syllable-spelling accuracy (BELO)	-.218	.277	.187	-.395	.378	–				
7. Word-spelling accuracy (BELO)	.058	.217	.543*	-.404	.306	.290	–			
8. Alphabet writing in 1 minute	-.350	.453	.544*	-.468*	.705**	.549*	.310	–		
9. Experimental task: spelling accuracy (word-dictation)	-.356	.504*	.711**	-.385	.486*	.340	.739**	.583**.	–	
10. Experimental task: handwriting quality (word-dictation)[a]	-.002	.112	-.085	.374	.145	-.230	-.035	-.075	-.264	–
11. Experimental task: handwriting speed (word-dictation)	-.133	.359	.284	.205	.253	.026	.080	.075	.139	.517*

Note. *$p < .05$. **$p < .01$

[a] Note for the interpretations of the correlations involving the handwriting quality scores: a higher score refers to a higher number of graphical errors, and a lower score refers to better handwriting quality.

Table 5

General Linear Mixed Model on Handwriting Variables

	Speed	Distortion	Size	Relative Height	Correction	Alignment
Turn-backs	-0.11	0.14	-0.09	-0.13	0.20	0.61
Angles	-0.41***	0.15	2.31**	3.9*	0.70	-0.15
X-Curves	-0.03	-0.07	-1.29*	-0.02	-1.02	-0.43
Y-Curves	-0.02	0.55	2.28***	0.04	0.91	2.5***
Mod. links	-0.02	4.08*	7.56***	9.22**	5.77	4.72*
Pen-ups	-0.06	0.42	1.15*	2.11	-0.60	1.27*
Length	0.00	0.18***	0.20***	0.30***	0.29***	0.22***

Note. $^*p < .05$. $^{**} p < .01$. $^{***}p < .001$. Mod. links = modified links.