Tools and Methods for Diagnosing Developmental Dysgraphia

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Handwriting is a complex perceptual motor task that requires years of training and practice before complete mastery. Its acquisition is crucial, since handwriting is the basis, together with reading, of the acquisition of higher-level skills such as spelling, grammar, syntax, and text composition. Despite the correct learning and practice of handwriting, some children never master this skill to a sufficient level. These handwriting deficits, referred to as developmental dysgraphia, can seriously impact the acquisition of other skills and thus the academic success of the child if they are not diagnosed and handled early.

Keywords: handwriting ; developmental dysgraphia ; product ; process ; daignosis ; child

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1. Handwriting: Acquisition and Role

Handwriting, considered language by hand, is a complex perceptual motor task involving attentional, perceptual, linguistic, and fine motor skills. It occupies a large proportion of children's daily activities at school [1][2] and is the basis, together with reading, of the acquisition of higher-level skills such as spelling, grammar, syntax, and text composition. A relationship between the mastery of handwriting movement and the quality of writing content has been established both at the semantic level in text production [3] and at the orthographic level in word formation [4]. If children pay too much attention to handwriting movements, they may have difficulties in the allocation of cognitive resources to higher-level processes.

From a developmental perspective, handwriting originates from drawing, from which it slowly differentiates as the child grows. In younger children, the quality of drawings is correlated to the quality of handwriting [5]. Then, with the acquisition of handwriting, this relationship between drawing quality and writing quality remains correlated but attenuates, with more discrepancies [6]. The formal acquisition of handwriting begins around the age of 5 at preschool, and its mastering requires about 10 years of practice and training.

2. Handwriting Deficits

Despite the correct learning and practice of handwriting, some children never master this skill to a sufficient level of automation (reviewed in [7][8][9]). These handwriting deficits, referred to as developmental dysgraphia in children, have been defined as a written-language disorder that concerns mechanical writing skills in children of average intelligence and with no distinct neurological or perceptual motor deficits [10]. Currently, dysgraphia is not recognized as a disorder per se in the Diagnostic and Statistical Manual of Mental Disorders, fifth edition (DSM-5) [11], or the International Classification of Diseases, 11th edition (ICD-11). The DSM-5 only mentions "deficits in the fine motricity required for handwriting" in the chapter dedicated to the development and evolution of learning disorders. Due to the diversity of methodological approaches and the absence of a consensual definition, the exact prevalence of dysgraphia is not known and probably differs between countries and writing systems.

Dysgraphia is generally found in association with neurodevelopmental disorders, namely dyslexia (DL), Developmental Coordination Disorder (DCD) and Attention Deficit Disorder/Hyperactivity Disorder (ADHD) [12][13][14][15][16][17]. Dysgraphia preferentially affects boys (3:1 ratio), most likely because of the prevalence of the associated disorders in boys [7][18]. Many studies have shown differences in handwriting deficits depending on the associated disorder [19][20][21][22][23][24][25]. DCD primarily affects handwriting quality [21][26][27] while DL affects both speed and, to a lesser extent, handwriting quality [25][28]. Children with comorbid DL and DCD present nearly the same profile of difficulties as children with DL, although with a much higher within-group variability. Comorbidity seems to lead to the addition of DCD and DL writing difficulties but without aggravation of the deficits in each of the two dimensions [23].

Dysgraphia can vary according to graphic and linguistic systems. Firstly, the perceptual and motor complexities of different graphic systems vary widely. Some graphic systems require many hours of practice to reach a comparable level of automation, while others are much easier to learn. For example, the Kanji system, which requires a minimum knowledge of 2136 essential kanji (*jōyō kanji*), according to the Japanese Ministry of Education, even though they are made up of a large number of strokes (up to 23 strokes for the most complex kanji), is much more complex than the Latin alphabet, which is based on 26 letters only. As a result, the risk of difficulty is much greater in the former than in the latter. Secondly, within the same graphic system, some linguistic systems are also more complex than others: in the grapheme–phoneme relationship, for example. Italian and English are examples of transparent and non-transparent languages, respectively, for which the amount of reading and writing practice can vary to reach the same level of expertise. Knowing the interaction between orthographic and graphomotor constraints [4], one may assume that the risk factor for developing dysgraphia is higher in the case of English than in the case of Italian, especially when dysgraphia is subsequent to dyslexia [29].

Given the central role of handwriting in the acquisition of other skills, these deficits can seriously hamper the acquisition of other skills [30][31][32]. It has been shown that, given equal content, the worst quotes are attributed to less legible school works [33], resulting in a decrease in the child's self-esteem. Dysgraphia may thus impact the academic success of a child if it is not diagnosed and handled early [34][35]. To this end, different tools are available to allow researchers and clinicians to analyze the two dimensions of handwriting: the final product and the dynamic process that generates the trace [36][37].

Evaluation of the handwriting product refers to the static, spatial features of the written trace. This kind of analysis is performed afterward. This is the principle of many tests used in different countries (for a review, see [7]). The quality of the trace is evaluated based on different features such as letter size and form, the spatial organization of handwriting on the paper sheet, margins, etc.

Evaluating the handwriting process refers to the analysis of the dynamic, kinematic, and temporal features of handwriting. Several types of variables can be analyzed, depending on the tools used for the evaluation: posture, finger and arm movements, pen grip and finger pressure on the pen, in-air and on-paper durations, pen velocity, pen pressure, etc. The increasing number of publications on the analysis of the handwriting process over the past years attests to the growing interest of researchers in this field (e.g., [38][39][40][41][42]).

3. Handwriting Tools Based on the Product

Although mainly designed for a developmental population (from the age of 5 onward), some diagnosis tools can also be used on adults up to the age of 80 (QNST-3; [43]). The test duration is variable, from a few minutes to up to 30 min. This parameter is interesting because deficits may not be visible during the first few minutes of handwriting but may appear during a continuous handwriting task, as is the case in the classroom. The tasks used in the tests are of three main types: copying a text or a sentence, writing under dictation (letters, digits, words, or text), and spontaneous writing. These complementary tasks explore different aspects of handwriting. The copy task is the easiest and can be used with beginner writers. Moreover, it resembles the condition of the classroom, where children are often asked to copy texts. However, the reading component can pose problems for children with dyslexia, introducing a possible bias in the interpretation of the test results. The dictation task is ecological too, without the reading component, but the spelling processes and the orthographic components may again pose problems for children with dyslexia. Finally, the spontaneous writing task is likely to be the most relevant. The difficulty here is the establishment of norms, since the texts produced are all unique. The general criteria of legibility and quality are thus used in this case, which may provide a less fine-grained analysis of handwriting.

It should be noted that one test includes an analysis of texts produced at school: the TOLH (Test of Legible Handwriting [44]). Two others include writing from memory: the ETCH-M (Evaluation Tool of Children's Handwriting—Manuscript [45]) and the MMHAP (Mac Master Handwriting Assessment Protocol [46]). Two tests also add another level of analysis thanks to two conditions in the copy task: normal speed and maximum speed (the DASH [47]). This approach is particularly interesting, since it mimics certain classroom conditions, and it is well-known that adding constraints (temporal or spatial) during handwriting helps reveal handwriting deficits [48][49]. Combining different tasks and/or conditions can provide a fine and detailed analysis of handwriting. It is worth noting that although these tasks are complementary, only three tests involve all three types: the BVSCO-3 [50], the ETCH-M [45], and the MMHAP [46].

The majority of the tests analyze handwriting quality using different criteria such as legibility, letter form, the spatial organization of letters or words, alignment, etc. Some tests also measure handwriting speed by evaluating the number of characters or letters (BHK [51]; French adaptation [52]; BHK-ado [53]; BVSCO-3 [50]; CHES-M [54]; ETCH-M [45]; EVEDP [55]; MMHAP [46]; MHA [56][57]) or the number of words produced in a fixed period of time (DASH [47]; EVEDP [55]). Since a universal, gold-standard test for the diagnosis of dysgraphia is not available, it is sometimes necessary to combine several tests to perform an optimal clinical assessment. The DASH test appears to be the most complete one, since it includes various types of tasks and different constraints of writing and it requires about 15 min of writing. Its weakness is that it only evaluates handwriting speed.

Finally, researchers should also mention the existence of questionnaires, which can be interesting to use to complement the other tests. Indeed, these questionnaires provide subjective information about the evaluation of handwriting quality by the teacher or the child, which can be useful in the perspective of a rehabilitation program. In addition, these questionnaires could also be used for the screening of children with handwriting difficulties on a larger scale. The Handwriting Proficiency Questionnaire (HPSQ [58]) has been developed in different languages for children from 7 to 14 years old. It has to be completed by adults (teachers or clinicians). An adaptation of this questionnaire, the HPSQ-C, was developed later to inform about a child's perception of his/her handwriting quality. This autoquestionnaire has been shown to be suitable for the identification of handwriting deficiency among school-aged children and to be appropriated for clinical use [59]. Likewise, the "questionnaire for children" [60] is an autoquestionnaire in which children self-report their handwriting quality and difficulties. It targets children from 1st to 5th grade, but only a French version is available.

These algorithms are all based on pattern recognition methods using images of letters, digits, words, or sentences. They use a large database of images from which the characteristic features of "poor writing" are extracted and analyzed using machine learning approaches. The performances of computer tools are evaluated using a series of criteria. Precision, also called the positive predictive value, is defined as the number of correct classifications of dysgraphic children divided by the total number of classifications. Sensitivity represents the true-positive detection rate (the correct classification of children with dysgraphia). Specificity represents the true-negative detection rate (the correct classification of typically developing children).

4. Handwriting Tools Based on the Process

Collecting the spatio–temporal characteristics of a written trace has become possible thanks to the development of digital tablets. The principle is simple: the tablet records the x, y, and sometimes z (up to 2 cm) positions of the pen with a high frequency (every 5 or 10 milliseconds), as well as the time, the pen pressure, and the angle of the pen to the tablet. From these data, a large variety of static (size, alignment…), kinematic (speed, acceleration, jerk…), and dynamic (pen pressure, pen tilt…) features can be calculated. To avoid the undesirable effects of loss of surface roughness (e.g., [1]), a sheet of paper must be attached to the digital tablet and an ink pen compatible with the tablet must be used.

Over the last decades, a growing number of studies have focused on the development of tools for the diagnosis of dysgraphia using digital tablets.

The different digital tools for the diagnosis of dysgraphia, combine dynamic, kinematic, and static features extracted from handwritten tracks. These features are then analyzed using mainly machine learning approaches to classify the data (i.e., classifiers). These tools differ by the natures of the tasks analyzed (handwriting or graphomotor tasks), the sizes of the datasets, and the computational approaches used to analyze the data.

Of the 22 studies reported here, four used graphomotor tasks; the others used handwriting alone or a combination of handwriting and drawings. It is interesting to mention that several studies have used tasks that have been validated in clinical practice, such as the BHK [38][61][62][63], the BVSCO2 [64], or the Minnesota Handwriting Assessment (MHA [65]).

The size of the dataset used varied between 35 and 580 participants, and the children included in the different studies were between 5 and 15 years of age.

Nine studies used classical statistical comparisons to identify discriminative features between groups. The others used different algorithms of machine learning (Random Forest, Support Vector Machine, Convolutional Neuron Network, etc.) to classify children into different groups. These methods are called "supervised learning approaches", since the algorithm was trained to identify groups that were previously labeled. Most of the studies reported here present a simplistic classification of children in two groups: with or without dysgraphia. Only one study classified the children into four groups: typically developing, with mild dysgraphia, with mean dysgraphia, and with severe dysgraphia [66]. This approach is interesting, since it considers dysgraphia as a continuum of severity. This is probably closer to reality than a dichotomic classification, as has been recently suggested by Lopez and Vaivre-Douret [67], who have described three levels of handwriting disorders in children from 1st to 5th grade: mild disorder, moderate disorder, and dysgraphia.

The tools based on the analysis of handwriting samples obtained the best classification performance. For example, Asselborn et al. [61] reached a sensitivity of 96.6% and a specificity of 99%, and Mekyska et al. [68] reached a sensitivity of 96%. It is worth noting, however, that the excellent performances obtained in [61] must be considered with caution, since they may be biased by the fact that the authors only included participants with severe dysgraphia [69]. The most discriminative features between children with and without dysgraphia varied among the studies but generally included a larger size in dysgraphic handwriting, numerous velocity variations, a lower mean speed, increased lift and stop duration, and variations in the pen angle to the tablet.

The tools based on the analysis of drawing samples appeared promising too, although their performances were slightly lower than of those based on handwriting. For instance, the algorithm developed by Mekyska et al. [70] obtained a sensitivity of 90%. The idea that dysgraphia can be identified based on graphomotor tasks suggests that it can be independent from higher-order processes, namely linguistic ones. Developing diagnostic tools based on drawings is interesting for two reasons: these tools would be more universal, since they are independent of the language and the alphabet, and they can be used with younger children to identify “at-risk” children, which could be handled earlier.

Developing a computer tool for the diagnosis of dysgraphia is not trivial. Several reasons can explain these differences. First, the variety of the tasks used and the number of participants led to large differences in the sizes of the databases, which was a critical determinant in a classifier’s performances. Second, a large panel of machine learning approaches was used, with different numbers of features analyzed among studies. Although certain classification methods appeared better than others (Random Forest, for example), none have currently reached excellent performances. Since the interest of researchers in these tools is growing, it seems obvious that their efficiency will rapidly be improved. To do so, however, a number of key elements will be important to consider. First, it will require the constitution of large databases of handwriting and drawing samples from children that are perfectly characterized from a clinical point of view. It will also be necessary to estimate the severity of dysgraphia and not only provide a dichotomic classification of children with or without dysgraphia, as proposed by Sihwi et al. [66]. Moreover, other processes involved in handwriting, such as visuomotor aspects, which are currently being investigated [71], would be interesting to include in future diagnostic tools. Finally, it is also worth noting that diagnostic tools fully integrated into the pen and using machine learning approaches are also under investigation [72][73][74].

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