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A New Approach to Diagnosis

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Developmental Dysgraphia: A New Approach to Diagnosis

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Abstract: Writing is a complex skill. Issues in this process, which are usually associated with developmental dysgraphia (DD), could consistently cause problems in everyday life, like for example, lower self-esteem and poorer academic achievement. That is why the correct diagnosis of DD is crucial for further child development. DD belongs to the category of specific learning disabilities and according to different studies, its prevalence ranges between 0.1 and 30 percent. Diagnosing a child with DD relies, in the first place, on teachers. After that, psychologists, or special educational specialists (in the Czech Republic) commonly use qualitative evaluation of the written process, where the child is observed when he or she is writing. Nevertheless, there are no objective tests or standardized examinations for the assessment of handwriting deficiency either in special educational or psychological practices. In the frame of current research, a new quantitative approach to handwriting proficiency assessment was developed. Digitizing tablets (Wacom Intuos Pro L) with a special inking pen (Wacom Ink Pen) are used to record the online handwriting process and graphomotor skills of children. Administration templates contain simple graphomotor elements and complex figures related to DD symptoms and cognitive (memory and visuospatial) abilities. This new approach to diagnose handwriting issues will be presented in this article.

Keywords: Developmental Dysgraphia, Diagnosis, Online Process, Machine Learning, Graphomotor Disabilities Rating Scale

Introduction

The aim of this article is to present the experimental research on graphomotor disabilities (GD) and developmental dysgraphia (DD) performed by an interdisciplinary team of psychologists, educationists, and engineers in Brno, Czech Republic. The main goal is to create an objective and accurate way to detect problems with handwriting and to help specialists in the practice of this method. In the first part of the article, GD and DD will be described and the problems with their existing definitions will be discussed. The second part will compare the methods of diagnosis of handwriting issues in the Czech Republic with those in the rest of the world, and the problems with the process of diagnosis in the Czech Republic will be clarified. In the third part, a new method will be presented—the graphomotor disabilities rating scale (GDRS)—which is currently being researched and developed.

There is a huge problem not only with diagnostic processes but with diagnostic methods themselves. Experts such as psychologists, occupational therapists, or teachers lack objective diagnostic methods to detect handwriting issues. One part of this problem is that there is a lack of research concerning this topic and that dysgraphia is marginalized. On the web, there are 12,120 results for the keyword "dyslexia" (reading disorder) and only 538 results for the keyword "dysgraphia" (writing disorder).

Theory and Current State

Graphomotor Skills and Handwriting

Graphomotor (GM) skills are psychomotor abilities which primarily comprise writing and drawing. The GM process is considered as an outcome of cognitive, motor, and perceptual skills

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and their interactions. Hence, if a child has issues with GM skills, there is a disruption between ideas and the ability to express them through writing. It is for this reason that writing has been described as “language by hand” by Berninger and her colleagues (2002). The action of writing by hand begins with ideation and planning processes, followed by the application of language rules (grammar, syntax, spelling, punctuation, etc.), with the outcome of text production at the motor level. The lower arm, wrist, and fingers must cooperate to create a final handwriting product. Moreover, other processes like evaluation and self-monitoring, which serve as effective feedback, must be taken into consideration. All of these look like they are consecutive processes, but in reality, they all take place concurrently.

Nowadays, nearly all models of handwriting (Van Galen 1991; Kandel et al. 2011; McCloskey and Rapp 2017; Feder and Majnemer 2007; Cornhill and Case-Smith 1996; Berninger and Amtmann 2003; Flower and Hayes 1981) differentiate between several levels, which could be summarized as: (1) higher cognitive levels and (2) lower motoric-perception levels. For example, one of the oldest theories developed by Flower and Hayes (1981) distinguishes between three levels of mental representation. At the conceptual level, the ideas or preverbal messages, stored in the long-term memory, are created during the planning processes. At the linguistic level, translating processes are involved, and preverbal messages are translated into verbal messages. This is how the conceptual structure from the first stage gets its grammatical properties (syntax, morphology, and spelling, stored in the mental lexicon). Finally, at the motor level, the verbal message is converted into a sequence of motor plans and the written output is created. It comprises the regulation of handwriting parameters such as size, speed, spacing, force–form alignment, and slant (Hayes and Gradwohl-Nash 1996; Bock and Levelt 1994; Kellogg 1996; McCloskey and Rapp 2017).

Feder and Majnemer (2007) described two components of the writing process: motor and perceptual. Perceptual components comprise sensory modalities, visual perception, and sustained attention. Motor components pertain to fine-motor control (in-hand manipulation, bilateral integration, motor planning, and kinesthesia). Both components are linked to visual–motor integration as an important part of the whole handwriting process, which is the ability to coordinate visual information with motor processes. Other authors (Christensen 2005; Medwell, Strand and Wray 2009) have agreed that writing is not only a motor skill. According to them, the memory and orthographic processes work together to recall the letter shapes and translate its patterns automatically. A central part of the writing model proposed by Berninger and Amtmann (2003) involves the working memory. It is linked to long-term memory through the process of composing and to short-term memory through the process of reviewing. The executive functions like conscious attention, planning, revising, and strategies for self-evaluation are involved as well. This model argues that orthographic–motor integration (OMI) contributes more to handwriting skills than fine-motor skills (Graham and Weintraub 1996; Abbott and Berninger 1993). The OMI allows the child to recall the correct shape of the letters or whole words from his or her mind and write it down without focusing attention on it. It means that the process of writing is automated. Research shows that OMI accounts for more than 50 percent of the variance in written language performance in individuals from primary through secondary school and even into adulthood (Bourdin and Fayol 2002; Graham et al. 1997; Jones and Christensen 1999).

As Palmis and her colleagues (2017) state, the automation of handwriting means that writing does not require conscious effort. Therefore, the cognitive resources could be allocated elsewhere, for example, to planning, organizing, or creating the content of the story (ideation). Automaticity is based on experience and training and so the movements become more fluent. At this point, the Matthew effect should be mentioned (Cunningham and Chen 2014; Stanovich 1993), which describes the improvement in the reading and/or writing skills of children who have a better level of those abilities, and conversely, stagnation among children who have poor skills. From previous paragraphs, it is evident that writing is not merely a motor process, but other higher cognitive and executive processes are also involved. Richards et al. (2011, 512) wrote that writing is a “brain-based skill that facilitates meaning-making as writers externalize their cognitions through letter forms, the building blocks of written words and text." From this point of view, handwriting issues and dysgraphia should not be seen only as a distortion of a written product, but we should be able to see those higher cognitive processes as well and incorporate them into the whole picture of the normal writing process and also into writing disabilities. For example, when the child must focus on the execution of motor plans (lower motoric perception functions), the working memory capacity is overloaded and there is no space for higher cognitive processes. Likewise, the automatization of writing is not possible in that kind of setting.

Developmental Dysgraphia and Its Diagnosis

DD is defined as the disturbance of the process of written production, which is related to the mechanics of handwriting. In ICD-10 (WHO 1992), the problems of handwriting belong to Chapter 5: Mental, behavioral, and neurodevelopmental disorders; Section F80-F89: Pervasive and specific developmental disorders; Category F81: Specific developmental disorders of scholastic skills; and the final code F81.81: Disorder of written expression. To define handwriting issues, the ICD-10 was used instead of the DSM-IV (APA 2000), because it is the common diagnostic system in Europe. Although there is a definition of this disorder, there are missing diagnostic criteria both in the ICD-10 and the DSM-IV. Moreover, in the literature, different terms are used for describing dysgraphia. A child could be dysgraphic or could be named as having poor handwriting. A child could have handwriting issues or difficulties and those could be part of special learning disorders or disabilities. Also, the motoric part of dysgraphia could be linked to agraphia or developmental coordination disorder**.** Children with DD are of at least average intelligence and they have not been identified as having any neurological problems (Hamstra-Bletz and Blöte 1990). The prevalence ranges between 10 and 34 percent (Döhla and Heim 2016; Cermak and Bissell 2014) depending on the country and study in question. The data reported in Czech Republic concern only specific learning disorders, with estimates ranging from 3 to 5 percent (Kejřová and Krejčová 2015; Zelinková 2015).

Another problem with diagnosis is that of comorbidity. Writing issues are present in 30 to 47 percent of children with reading issues (Chung, Patel and Nizami 2020). Authors added that there are 90 to 98 percent children with neurodevelopmental issues such as attention-deficit hyperactivity disorder or autism, who also struggle with handwriting. It is also the case that developmental coordination disorder affects the handwriting process. In the Czech Republic, the numbers of comorbidities with other specific learning disorders are missing in the data.

Usually, the following symptoms are listed: (1) problems with size control—letters are not consistent in size; (2) slant—written letters are not even; (3) alignment—child is not able to follow the lines; (4) pressure—too high, usually linked to incorrect grip which causes fatigue or pain during the writing; (5) poor spacing between letters and words; (6) messy organization of the text on the page; (6) problems with letter differentiation and spelling—inversions of b and d, a and o, etc.; (7) added or missing strokes; (8) problems with beginning of writing—child does not know where or how to start; (9) grammar mistakes—child does not check the outcome or she/he erases or crosses out the text a lot. According to the literature (Rosenblum, Weiss, and Parush 2003) there are two main outcomes which are used for assessing and defining poor handwriting: (1) legibility, which is the combination of all the above-mentioned symptoms, and (2) performance time, which could be assessed as writing duration.

Diagnostic Process

The primary aim of researchers in this area is to develop standardized evaluation capable of producing quantitative scores for handwriting quality. The dilemma is how to define "readability" or "quality of handwriting" (Ayres 1912). Rosenblum, Weiss, and Parush (2003) distinguished two types of evaluation: product and process evaluation. To enhance the methodology, questionnaires were implemented as a third type.

First, there is product evaluation. As the name suggests, in this case, final and static outcomes of written products are evaluated by experts. This evaluation is based on two types of scales: (1) global and (2) analytical. Global scales consist solely of one factor, legibility, which means that the assessment is based on an overall judgment of this factor. Analytical scales are created with many criteria such as the shape of letters, spacing, or speed. In this approach, these specific features are linked to the general legibility of writing. In practice, there are different tests which serve this purpose. An overview of common tests used for diagnosing handwriting problems is shown in Table 1 (Feder and Majnemer 2003; Roston, Hinojosa, and Kaplan 2008). The major drawback of these tools is a lack of evaluation of psychometric qualities (see validity rows). Only the TOHL (Test of Legible Handwriting; Larsen and Hammill 1989) has documented evidence for criterion, content, and construct validity, but the test itself was designed in 1989.

In the last 20 years, there has been a new approach called process evaluation, where computerized technology, software, and digitizers, are used to record the process of handwriting itself (Rosenblum, Weiss, and Parush 2003; Longstaff and Heath 1997). This interdisciplinary field, called graphonomics, focuses on handwriting movement analysis (e.g., Van Gemmert and Teulings 2006). Most importantly, this approach addresses the limitations of previous measurement tools. In addition, as the child is writing on the paper with inking pen, it maintains the measure as ecologically valid. This online process records not only the process, but it also allows the researcher to measure the features which underlie writing, and which are not detectable by the naked eye. That is why this quantitative online examination is considered to be more precise and objective. Unfortunately, the diagnostic tool which should be established on the outcomes of these online and objective measurements does not exist yet. As a consequence, although there have been studies with promising outcomes (e.g., Asselborn, Chapatte and Dillenbourg 2020), actual diagnostic applications have not yet been pursued.

A third approach is evaluations using questionnaires, where the children judge themselves (self-evaluation) or are judged by others (teachers, parents, psychologists, etc.). These questionnaires are usually focused on different manifestations of handwriting issues or on experiences of disability and well-being. Handwriting problems are evaluated from a subjective point of view without assessing the handwriting itself, contrary to product evaluation. An example is the Handwriting Proficiency Screening Questionnaire for Children (HPSQ-C; Rosenblum and Gafni-Lachter 2015).

Having covered the different approaches to handwriting analysis, a description of the diagnostic process from an expert's point of view will ensue. The profession of occupational therapy is, among other things, responsible for correct GD and DD assessment and remediation in many jurisdictions. In the Czech Republic, the diagnosis process is distributed between teams of psychologists and a special educationist (SE) who takes part in the process. Working in collaboration, the psychologists are responsible for taking anamnesis and for testing intelligence and memory. Further diagnosis, especially of specific learning disorders (e.g., dyslexia, dysgraphia, dyscalculia, etc.), is carried out by a SE. When a diagnosis of dysgraphia is returned, the SE assesses the child in several ways:

1) writing assessment, which is created from a transcription task (cursive writing → cursive writing), a copying task (block letters → cursive writing), a dictation task, and/or drawing;
2) experienced but subjective observation during the writing process, which includes observation of (a) how the child is sitting during writing, (b) the grip, i.e., how the child is holding a pen or pencil, (c) the relaxation of hand during writing, (d) how the child is writing, i.e., the stroke smoothness, pressure, size of the letters, slant, etc., (e) speed of writing, (f) jerky movements, (g) increased focus on writing process, which could cause more grammar mistakes;
3) test of laterality or handedness;
4) visual perception;
5) right-to-left and spatial orientation;
6) analysis of homework and exercise books (Pokorná 2015; Zelinková 2015).

On looking at these criteria, we perceive several problems. Firstly, there is no screening tool in the Czech Republic for teachers or parents, who often first recognize handwriting issues. Neither do the practitioners have a specialized test for detecting or diagnosing handwriting issues, but as has been noted previously, nor are current, internationally used tests dependable, as they have questionable or unknown psychometric properties. The graphonomics approach is also yet to yield a diagnostic tool, while the questionnaire approach relies on subjective and nonuniform criteria for evaluating handwriting issues. For the latter, even when special educationists are experts in their field, there could be inconsistent outcomes from the diagnostic process.

Table 1: Summary of the Handwriting Evaluation Tests and its Psychometric Properties

	MHA	*ETCH-M*	*CHES-M*	*DRHP*	*TOLH*	*DHA*	*WOLD*	*THS-R*	*HHE*	*DASH*	*BHK*	*HST*
Age								6–18		9–16	6–12	3–12
Grade	1–2	2	2	3+	2–12	3–8	1–5		2–3			
Standards	✓				✓			✓		✓		✓
Alphabet writing	✓	✓				✓		✓	✓	✓		
Numeral writing		✓										
Near-point copying	✓	✓	✓			✓		✓	✓	✓	✓	✓
Far-point copying		✓				✓						
Dictation		✓				✓		✓	✓			
Composition		✓		✓	✓							
Speed	✓	✓	✓				✓		✓	✓	✓	✓
Global readability	✓	✓	✓		✓		✓	✓	✓		✓	
Inter-rater	0.87 – 0.98	0.75 – 0.92	0.85 – 0.93 ICC	0.61 – 0.65	0.95				0.75 – 0.79	0.85 – 0.99 ICC	0.71 – 0.89	0.99 ICC
Test-retest	0.58 – 0.94	0.63 – 0.77	×	×	0.90			0.82		0.50 – 0.92 ICC	0.51 – 0.55	0.99 ICC
Criterion	×	×	×	✓	✓	×	×	✓	×	×	×	×
Construct	×	×	×	×	✓	×	×	×	✓	×	×	×
Content	✓	✓	×	×	✓	×	×	×	×	✓	×	×

Notes: MHA: Minnesota Handwriting Assessment (Reisman 1993); ETCH-M: Evaluation Tool for Children's Handwriting-Manuscript (Amundson 1995); CHES-M: Children's Handwriting Evaluation Scale-Manuscript (Phelps and Stempel 1988); DRHP: Diagnosis and Remediation of Handwriting problems (Stott, Moyes and Henderson 1985); TOLH: Test of Legible Handwriting (Larsen and Hammill 1989); DHA: Denver Handwriting Analysis (Anderson 1983); WOLD: –Wold Sentence Copy Test (Maples 2003); THS-R: Test of Handwriting (Milone 2007); HHE (Erez and Parush 1999); DASH (Barnett et al. 2007); BHK (Hamstra-Bletz, DeBie, and Den Brinker 1987); HST (Wallen, Bonney and Lennox 1996).
Source: MHA-TOHL: Feder and Majnemer 2003; DHA-WOLD: Roston, Hinojosa, and Kaplan 2008

New Diagnostic Approach

Planned Sample

In the research project, children were enrolled via psychological counselling centers and via schools. The sample is divided into three groups: (1) children with diagnosed dysgraphia; (2) children who were not diagnosed, but the teachers or children themselves reported some problems with handwriting; and (3) typical development children. The sample consists of children from kindergarten to fourth grade, which makes five groups. There are 100 children planned for each group, that is, there should be approximately 500 children in the whole sample. Previous studies used only small samples, with approximately 20 children in each group on average (experimental/comparative) (e.g., Engel-Yeger, Nagauker-Yanuv, and Rosenblum 2009; Smits-Engelsman and Van Galen 1997).

With this type of sample distribution, differences between groups could be compared in three ways: (1) horizontally—between the condition of age/grade (five levels); (2) vertically—between the condition of diagnosis (three levels); (3) and a combination of the two conditions. The first axis of comparison is very important, because the internalization of the writing process is believed to occur between the third and fourth grades. It means that this process becomes more automatic, and attention becomes more focused on the process of ideation and the content of the text, which frees up capacity for the working memory (McCutchen 1996). Furthermore, changes or improvements in the writing could be tracked. Some studies suggest that handwriting characteristics of typical development in children should be smaller, of even size, and smoother (Meulenbroek and Van Galen 1989; Zesiger, Mounoud, and Hauert 1993). Older children also use less bounded cursive writing, but the letters are closer (Blöte and Hamstra-Bletz 1991).

Instruments: Digitizer and Software

For the research, the specially created software HandAQUS for handwriting acquisition is used together with digitizing tablets (Wacom Intuos Pro L) with a special inking pen (Wacom Ink Pen). This system allowed the researchers to capture information about the position of the pen (x and y axes) on the tablet's surface or up to 1.5 cm above it. It also allowed the measurement of pressure on the surface, the pen's tilt, and azimuth. Finally, the movement was sampled with 150 Hz sampling frequency, where each sample was associated with a time stamp, which enabled the reconstruction of kinematic characteristics. More specifically, it distinguishes between several categories of conventional handwriting features (Table 2).

Table 2: List of Clinical Features Used in the Study

Category/Features	*On-surface*			*In-air*		
Temporal	Global	Vertical	Horizontal	Global	Vertical	Horizontal
Duration of handwriting	✓			✓		
Spatial	Global	Vertical	Horizontal	Global	Vertical	Horizontal
Height of written product	✓			✓		
Width of written product	✓			✓		
Angle of written product	✓			✓		
Height of stroke	✓			✓		
Width of stroke	✓			✓		
Angle of stroke	✓			✓		
Kinematic	Global	Vertical	Horizontal	Global	Vertical	Horizontal
Velocity	✓	✓	✓	✓	✓	✓
Acceleration	✓	✓	✓	✓	✓	✓
Jerk	✓	✓	✓	✓	✓	✓
Dynamic	Global	Vertical	Horizontal	Global	Vertical	Horizontal
Pressure	✓					
Altitude	✓			✓		
Azimuth	✓			✓		
Other	Global	Vertical	Horizontal	Global	Vertical	Horizontal
Number of pen elevations	–	–	–	–	–	–
Number of changes in velocity	✓	✓	✓	✓	✓	✓

Source: Mekyska

The Protocol

The protocol for this study was created by a SE with extensive experience in diagnosing special learning disabilities, who is also the author of several remediation publications (e.g., Bednářová and Šmardová 2006; Bednářová 2017). All tasks were designed taking into consideration the different grades, as the complexity and difficulty were gradually increased. The assessment took approximately 50 minutes depending on the specific sample conditions. Overall, the protocol consisted of three types of tasks:

1) Seven graphomotor elements (see Figure 1): These represent the basic forms of Latin cursive letters, and for kindergarten children and first graders they are usually the very first attempt to create more complex graphomotor manifestations. For example, in this exercise the differences between the first and the second Archimedean spirals are noted. With the second one, it is more difficult to perform fine-motor movements because the loops are closer together. The last task is also very hard to accomplish for younger children, because contrary to the previous tasks the child has to use spatial abilities and combine the upper and lower loops (Mekyska et al. 2019).

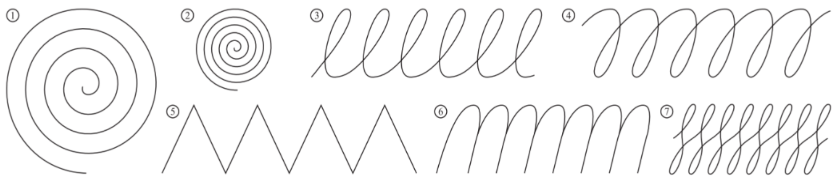

Figure 1: Examples of Graphomotor Elements
Source: Bednářová and Mekyska

2) Four sets of tasks for assessing cognitive processes (see Figure 2): These are intended to examine visuospatial abilities and working memory. In the first set of tasks, the child is asked to copy the figure into the empty box as precisely as she or he can (Task 8 in Figure 2). Immediately after that the assessor covers the upper part (the pattern and the copy) and the child is asked to draw the figure from memory (Task 9 in Figure 2). The same principle is applied to the remaining four tasks. The second set of four tasks is very similar to the previous one, where the child is asked to copy the complex figures to empty boxes (Task 18 in Figure 2). The principle of the third set is to draw five reverse figures (tasks 22 and 24 in Figure 2). The last task is based on the Rey-Osterreith complex figure principle (Rey 1959) where the child is asked to copy the complex figure (Task 27 in Figure 2), and after three minutes the child must recall the figure and draw it again (Task 28 in Figure 2).

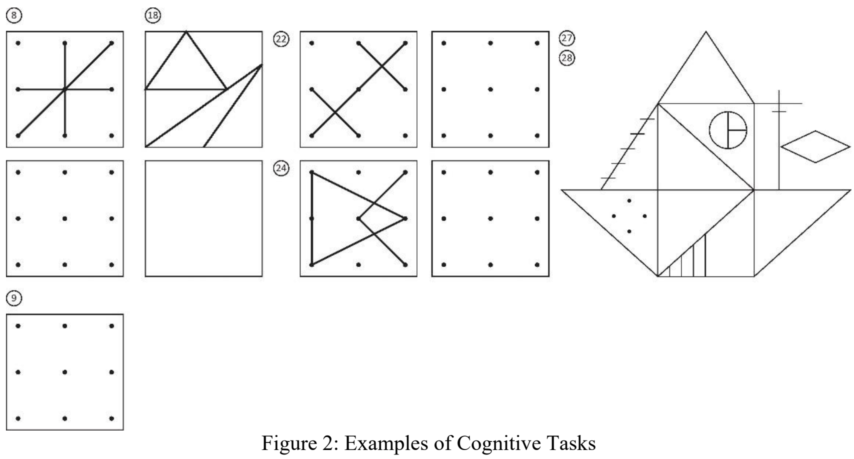

Figure 2: Examples of Cognitive Tasks
Source: Bednářová and Mekyska

3) Four sets of writing tasks: These were used to assess the handwriting process. Firstly, the child is asked for her or his signature. After this, the copying task follows, where the child copies one sentence from cursive script into cursive writing. The third task is a transcription one, where the child transcribes sentences from block letters to cursive writing, and the last one is a dictation task. According to some studies (Fryburg 1997; Margolin 1984; Parush et al. 2010), there should be differences between these types of tasks, because copying and transcriptions are based on processes where the inputs (stimuli) and outputs (final product) are visual. In the dictation task, the input is auditory, and the output is visual.

During the assessment, anamnestic data are taken to control demographic variables, such as age, sex, class, native language, parents' level of education, number of children in the family, and grades (Czech language, English language, Math); other disabilities, such as special learning disabilities diagnosis or other conditions (neurological, psychiatry, orthopedics, etc.). In addition, the Handwriting Proficiency Screening Questionnaire for Children (HPSQ-C; Rosenblum and Gafni-Lachter 2015) is used to check the child's self-evaluation. It contains ten items grouped in three factors: (1) legibility, (2) performance time, and (3) physical and emotional well-being. Every item is scored on a 5-point Likert scale (0 = never; 4 = always) and the total score is computed as the sum of points for each item. In the Czech sample, the mean is 12.86 with a standard deviation of ± 5.68. Based on this, two cut-off scores were created: the lower cut-off is 7 and the upper cut-off score is 19 (Šafárová et al. 2020).

Case Studies

Because the research is still ongoing, an example of a comparison between two children will be presented in the form of case studies. Children were chosen for this part of the study based on three criteria: (1) diagnosis, (2) HPSQ-C score, and (3) the classification provided by an expert. One child is a boy in the fourth grade from the experimental group with diagnosed dysgraphia (hereinafter DYS) and with a HPSQ-C score of 22. His scores for single HPSQ-C factors are: (1) legibility = 5; (2) performance time = 6; (3) physical and emotional well-being = 11. The other child is a girl in the fourth grade from the control group with typical handwriting development (hereinafter THD) with a HPSQ-C score of 5. Her scores for single HPSQ-C factors are: (1) legibility = 1; (2) performance time = 3; (3) physical and emotional well-being = 1. The DYS boy perceived his handwriting as less readable, it takes him more time to copy or write something, and he is not comfortable with the whole process of handwriting (e.g., feels pain, does not want to write, or feels tired).

The final output from the software is shown in Figure 3. The children are asked to transcribe the following text: Gusta, Lenka, Hana, and Stáňa are classmates. They will get a school report soon. After vacations they will attend the fourth grade. This text is a translation from the Czech version and Gusta, Lenka, Hana, and Stáňa are common Czech names. They were chosen for this task because the handwritten capital letters G, L, H, and S are difficult to remember and write for children with handwriting issues. In each image, the trajectory of the pen on the surface is depicted with blue lines and the trajectory of the pen in-air above the surface is depicted with red lines. In addition, in both figures, the pressure is represented by different shades of blue. Dark blue represents more pressure and light blue represents less pressure on the surface of the digitizer.

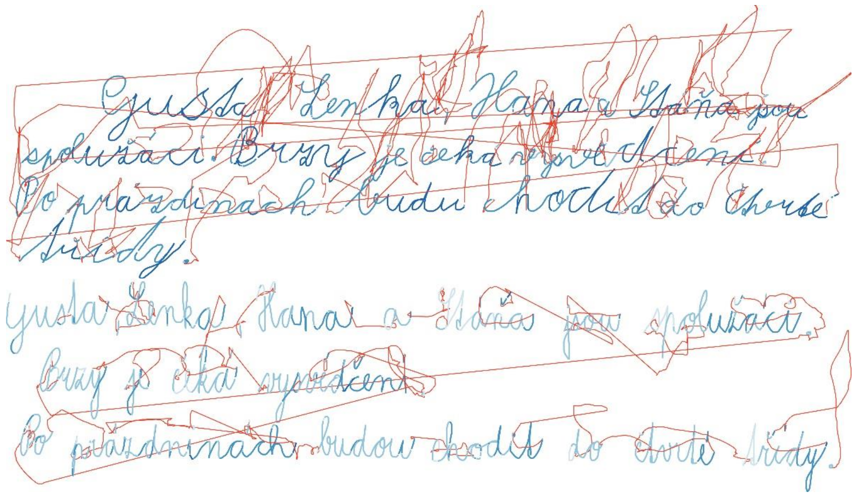

Figure 3: Comparison of Handwriting from the Transcription Task of the DYS Child (upper image) and THD Child (lower image)
Source: Zvončák

It is evident that the first writing sample is that of a child with handwriting issues. The letters are not even, they differ in size and slant, there are incorrect forms, the diacritics are missing, and there are missing letters. At first glance from a clinical point of view, it is obvious that the script is harder to read. However, with the new approach, it was found out that the DYS child spent significantly much more time in-air than the THD child (see red lines). The study showed that children with dysgraphia tend to have much longer in-air trajectories (Rosenblum, Parush, and Weiss 2003b) as they think longer about what the letter looks like and how to write it. This previously unrecognized phenomenon may indicate problems with the working memory and orthographic coding of graphemes. It also allows us to look at how the child thinks about the organization of the overall written text on the page.

Table 3 shows the values recorded for different handwriting features. In the first column, there is a differentiation between on-surface and in-air movements, corresponding with the blue lines (on-surface) and red lines (in-air) from both texts depicted in Figure 3. The features are divided into two categories, one quantifying the overall product (text) and the other quantifying particular strokes.

Table 3: Selected Handwriting Features of One DYS and One THD Child

		THD	DYS
Features of Whole Text			
On-surface	Width	49.29	63.52
	Height	192.23	250.42
	Length	2,636.84	4,107.46
	Duration	113.48	136.68
In-air	Width	46.88	79.34
	Height	194.66	257.25
	Length	1,838.15	4,857.65
	Duration	47.11	87.78
	Number of interruptions	98.00	124.00
	Mean of pressure	0.41	0.78
	Azimuth	1,220.47	1,142.45
	Altitude	568.80	672.04
Features of Strokes (Mean)			
On-surface	Width	7.92	11.65
	Height	5.91	5.90
	Length	37.69	40.78
	Duration	2.27	2.17

		THD	DYS
Features of Strokes (Mean)			
In-air	Width	16.93	27.76
	Height	7.49	16.20
	Length	29.33	67.67
	Duration	0.96	1.42
On-surface	Speed	14.58	17.49
	Velocity	16.68	18.88
	Acceleration	24.81	31.30
	Jerk	5,458.77	6,126.42
In-air	Speed	30.07	49.42
	Velocity	29.17	50.49
	Acceleration	−2.84	−111.53
	Jerk	19,289.18	−2,182.68

Source: Šafárová

Firstly, the focus will be on spatial features (given in millimeters) and the temporal features (given in seconds). The on-surface values demonstrate that the whole text of the DYS child is wider and higher, and that the overall trajectory of the written text is longer than that of the THD child. The same results concerning the mean width, height, and length of all strokes could be seen. By stroke is meant one continuous movement of the pen. One stroke can correspond to one letter, a group of letters, or even a whole word.

Also, the DYS child takes longer to complete the whole task, which indicates possible writing problems. Between the third and fourth grades of elementary school, children´s writing becomes smaller and faster. Dysgraphic children write significantly slower, and their font is large. At the same time, problems with fine-motor skills (vertical hand movements made up mainly of fingertips—height of strokes) and coarse-motor skills (horizontal hand movement made up of wrist—width of stroke) can be considered. These differences between the children described here are further accentuated by the spatial and temporal parameters above the paper surface.

The kinematic parameters are lower for the THD child. A higher value of velocity means that the task is written faster. Higher acceleration indicates higher fluctuation in the velocity of writing and the jerk feature refers to impulsiveness in writing and to the degree of sketching. From previous information, it may be concluded that the DYS child wrote the task much faster, with fewer fluctuations in speed (i.e., with less dynamics) and more sketching. However, some children without diagnosed problems have the opposite results. It can therefore be concluded that these children are slow writers because they are too focused on trying to make the script neater.

Dynamic features are represented by the pressure, altitude, and azimuth of the pen. It can be seen in the selected case that the DYS child had exerted more pressure on the tip of the pen on the surface of digitizer (see Figure 3, darker blue trajectory). Usually, clinicians or teachers report that children with dysgraphia have higher pressure but Rosenblum and Dror (2017) did not find any differences in pressure between children with and without developmental dysgraphia. The altitude parameter determines the angle between the surface and the pen. When the pen lies on the surface it is represented by 0°, and when the pen is perpendicular it is represented by 90°. The azimuth parameter specifies the position of the pen on the circle. At present, it is generally accepted that grip does not have a relationship with handwriting problems (Burton and Dancisak 2000; Sassoon, Nimmo-Smith and Wing 1986; Schwellnus et al. 2012).

Table 3 shows that the THD child interrupted the writing process several times during transcription. While it might seem that this is more typical for dysgraphic children (Chang and Yu 2013), Blöte and Hamstra-Bletz (1991) found out that in girls, especially during the automation of writing and during the creation of their own manuscript, cursive script is abandoned and there are gaps between individual letters—that is, the child makes more movements that are processed faster.

In addition, the coefficient of variation was used to compare the dynamic features between the children, which allowed us to examine differences in movement variability. Table 4 presents that the DYS child had higher variances of overall and in-air azimuth values. This means that the DYS child produced more circular movements. In addition, these differences are even more significant in air. This could be interpreted in the way that the DYS child had a problem with controlling the pen when the pen is above the surface. On the contrary, the THD child had higher variances of altitude values. That means that the variability of angles between the pen and surface is higher. The combination of both parameters could be understood as an indicator of fine-motor movements. If the position of the pen during writing is correct, the thumb and middle finger are used for creating the fine-motor movements and the index finger is used for stabilization. With the correct grip, during the writing the pen is oscillating back and forth, which causes altitude changes, but the position of the pen is more or less steady, which means no or minor azimuth changes. This combination could be seen in the handwriting of the THD child.

Table 4: Coefficients of Variation for Dynamic Parameters of One DYS and One THD Child

Dynamic Parameters	Coefficient of Variation	THD	DYS
Azimuth	Overall	0.24	0.43
	In-air	0.43	0.63
	On-surface	0.09	0.07
Altitude	Overall	0.17	0.15
	In-air	0.26	0.14
	On-surface	0.07	0.06
Pressure	Overall	0.65	0.71

Source: Šafárová

At this point it should be emphasized that the values used in the comparison of case studies are just absolute values. For some parameters (i.e., dynamic features), it will be suitable to use standard deviations or coefficient of variations because they indicate the variability in the writing process. Handwriting is a very dynamic process and in future research the focus should be on variances or changes in writing, instead of simple parameters. Lurija (1973) called the process of writing as a kinetic melody, which is apt. For those reasons it is necessary to search for and create new parameters or use the parameters from other fields of biosignal detection, or to explore the interactions between current parameters.

The Diagnostic Application: Graphomotor Disabilities Rating Scale

The general goal of the ongoing research project is to combine the process-oriented approach and the psychometric approach to create a new concept of objective GD and DD diagnosis and rating based on quantitative analysis of online handwriting. The outcome will be the graphomotor abilities rating scale (GDRS). Discrepancies between theoretical claims (e.g., dysgraphic children have problematic grip or are slower writers) and recorded clinical features will be further examined. Also, novel and nonconventional parameters, which will be able to better quantify motor skills and cognitive abilities, will be designed, as was presented in this article. Furthermore, mathematical models and machine learning that will calculate the GD score based on parameters and sociodemographic data are established. When completed, the project will produce a new DD scale, with a final score used as a rate of GD, rather than a binary classification (diagnosed/typical development).

Summary

This article referred to the current problematic state of diagnosing dysgraphia and explained that even when the disorder of written expression is defined by ICD-10 or DSM-IV, good diagnostic criteria are still missing (APA 2000; WHO 1992). Also, the relative lack of scientific interest in this topic in contrast with the related but more well-known condition of dyslexia was outlined. Present worldwide methods for measuring problems with handwriting are product-oriented and do not have sufficiently established psychometric characteristics or follow old norms and standardizations. Although there exists a possible process-oriented technique of measurement, this is currently not yet at the stage of being applied to diagnostic work. Moreover, in the Czech Republic there are no good methods specific for the Czech context for diagnosing handwriting problems. Collectively, these issues may result in the inconsistent evaluation of children with handwriting issues.

This discussion implies that a more objective assessment is needed. In the current work, process-oriented online assessment is applied. For this project, collaborating experts have created a new protocol which uses performance in tasks like graphomotor elements and complex figures to examine not only the handwriting process but also cognition (visuospatial abilities and working memory). The sampling strategy assumed distributions according to grades and diagnostic condition and included children who do not have any current diagnosis. The plan is to collect a larger sample size than has been used in similar previous research.

The main goal of the project is to create a graphomotor abilities rating scale (GASR). The GASR will be based on selected graphomotor, cognitive, and writing tasks which will distinguish among children with different degrees of handwriting difficulties. Using clinical, anamnestic, and digitally captured mechanical properties, a mathematical model will be built, which can then be used to compute scores for different categories of features (temporal, kinetics, etc.) and generate a final score so as to place a child along a scale. We think this would be an important step in generating a practical application from the research.

In this article, the new approach using data from two children who were sampled (DYS and THD) was illustrated. Comparison of these results showed that the DYS boy perceived himself as having less readable handwriting, taking more time to copy or write something, and being uncomfortable with the whole process of handwriting (e.g., feeling pain, not wanting to write, or feeling tired). From a mechanical and orthographic point of view, the DYS child's text was higher and wider on the page and it took more time to finish the writing task, with this excess duration reflecting in both on-surface and in-air measurements. The DYS child also made more interruptions during writing and exerted more pressure on the tip of the pen. Moreover, the DYS child wrote the task much faster, with fewer fluctuations in speed (i.e., with less dynamics), and more jerks. Some of these observations correspond with the classical picture of handwriting problems denoted in the literature, like for example, children with poor handwriting are slower writers (Rosenblum, Parush, and Weiss 2003a), spending more time in-air (Rosenblum, Parush, and Weiss 2003b; Rosenblum and Dror 2017), making more pauses or interruptions (Chang and Yu 2013); but some did not fit existing notions, like for example, less fluctuation in speed (Danna, Paz-Villagrán, and Velay 2013).

The field needs a better understanding of measured parameters and its relationships to create a meaningful picture of handwriting issues. This is because there are findings in the literature that seem to contradict claims made by other scholars, such as the influence of incorrect grip (Burton and Dancisak 2000; Sassoon, Nimmo-Smith, and Wing 1986; Schwellnus et al. 2012) or handedness (Ziviani and Elkins 1986). We hope that the ongoing research will enable others to empirically test some of the ideas presented in this article and contribute to the outstanding questions raised by other studies.

The case studies presented here, as well as the rest of the larger research project, have several limitations. First of all, given that it is the case that intact intelligence has been used as a rule-of-thumb to detect dysgraphia, we have chosen not to control for IQ. However, the sample was enrolled from: (1) elementary schools, which usually do not admit children with intellectual disabilities; and (2) special centers, where a diagnosis of mental retardation is an exclusion criterion for a diagnosis of dysgraphia. Given this, this limitation should not have a significant impact on the results. Another limitation is missing sociodemographic data of some of the children in the cohort. In some of the special centers, they are dealing with the European General Data Protection Regulation, known as the GDPR policy. This law enables counselling centers to share information about the children.

First, the process of handwriting itself should be mapped, as must its development and issues, and interindividual differences. Based on this, a new scale—the GDRS—will be created. At this point in the current research, the different settings of the feature groups (temporal, kinetics, etc.) are being investigated as there could be different combinations of dysgraphic issues. We hope that this scale will be helpful for professionals (special educationists and/or occupational therapists). Thus, the very first step should be to have a valid method for diagnosing, which will be also reliable. Subsequent work could then focus on remediation and therapy. With knowledge about the process and its development, researchers would be able to concentrate on the child's improvements or on contextual variables.

Problems with handwriting and graphomotor issues are long-standing and even today with computers and other smart devices, fine-motor movements are indispensable. Furthermore, writing continues to be a daily routine at schools as a significant part of the school day. Problems with writing are related not only to quantity and quality of written expression (Graham 1990), but with the child's academic achievement, which is usually assessed by her or his handwriting. Studies point to the relationship between worse grades and handwriting neatness (Brackett et al. 2013; Briggs 1980; Chase 1986; Graham, Harris, and Fink 2000; Hammerschmidt and Sudsawad 2004; Klein and Taub 2005). This approach could affect the child's self-esteem and well-being. In conclusion, if we want to offer these children better targeted care (remediation), we should understand their specific difficulties; this understanding is, of course, related to correct diagnosis.

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