

The Impact of Speed and Scale on Spiral Drawing in Children with Developmental Dysgraphia

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Abstract— Developmental dysgraphia (DD) is characterized by impaired handwriting fluency and motor control. While graphomotor deficits in DD are well-documented, the impact of movement scale and speed remains underexplored. This study examines how children with DD adapt to drawing spirals of different sizes under explicit time constraints, aiming to identify key motor impairments. We enrolled 269 children (3rd and 4th grade of primary school) who completed two Archimedean spirals (big and small) as quickly as possible. We then extracted features assessing fluency, velocity, and spiral regularity. Statistical and classification analyses were applied to identify key distinguishing features between children with DD and their typically developing peers. Results indicate that children with DD exhibited significantly higher velocity and more frequent velocity fluctuations in the small spiral. A classification model based on small spiral features achieved a balanced accuracy of 61%, with a sensitivity of 77% and a specificity of 45%. Our findings suggest that increased movement speed in DD does not indicate motor fluency but rather reflects reduced control and automation. The significant role of movement scale in graphomotor execution suggests that fine motor deficits in DD become more pronounced in tasks requiring higher precision. These insights contribute to a better understanding of the motor basis of DD and support the development of decision-support systems for graphomotor difficulties.

Keywords— *developmental dysgraphia, graphomotor disabilities, spiral, online handwriting, speed, scale*

I. INTRODUCTION

Developmental dysgraphia (DD) is a specific learning disorder characterized by impaired handwriting fluency and legibility despite adequate cognitive abilities [1]. Affected children struggle with both letter formation and broader graphomotor tasks, exhibiting, for example, increased variability in speed (generally, disfluent handwriting), longer in-air time periods, unstable pressure, etc. [2]. Research consistently shows that children with DD produce writing and drawing movements that are less automated, requiring greater effort and control than their typically developing peers [3], [4]. These motor inefficiencies not only affect academic performance but also impact children's self-esteem and motivation to engage in writing tasks, often leading to avoidance behaviors and frustration [1], [5].

To disentangle motor deficits from linguistic difficulties, studies have examined non-linguistic drawing tasks such as loops and spirals, which engage fine visuo-motor integration without orthographic demands [6], [7]. Children with DD generally show less fluid execution of these elements, with increased velocity fluctuations and motor hesitations. For example, upper loop drawing studies indicate that children with DD struggle to maintain consistent stroke size and spacing, often producing hyper-controlled, rigid movements [6]. Similarly, Archimedean spiral drawing has been identified as a sensitive tool for assessing motor irregularities, with children with DD displaying greater spatial inconsistency and reduced fluency compared to controls [8]. These findings support the notion that DD is not merely a handwriting issue but a broader motor coordination challenge with implications for other fine motor tasks.

However, key gaps remain in the literature. First, while dysgraphic handwriting deficits are well documented, the impact of movement scale (e.g., large vs. small graphomotor elements) has not been systematically explored. For example, drawing a small Archimedean spiral requires fine motor precision, whereas a large one relies more on gross motor coordination. Understanding whether dysgraphia-related impairments are more pronounced at a specific movement scale can provide insight into the nature of motor deficits. Additionally, differences in muscle control and spatial planning may contribute to variations in performance, suggesting that the role of proprioceptive feedback in dysgraphic motor execution warrants further investigation [9].

Second, few studies have examined how children with DD adjust under explicit speed constraints. When asked to draw as quickly as possible, do they fail to speed up, suggesting motor rigidity, or do they increase speed at the expense of accuracy? Addressing this question could provide important insights into whether DD stems from an intrinsic motor timing issue or a compensatory strategy to maintain speed despite impaired fine motor skills.

Therefore, this study aims to address these knowledge gaps by comparing the performance of children with DD and typically developing controls in a quickly drawn Archimedean spiral, focusing on the interaction between diagnosis and drawing scale. We hypothesize that, in comparison to their typically developing peers, children with DD will show greater performance deficits (lower fluency, increased irregularity, and faster execution) when drawing small spirals, as the smaller spiral requires finer motor control, which is particularly impaired in DD.

II. MATERIALS AND METHODS

A. Database

We enrolled 269 children (age 9.1 ± 0.5 years for the 3rd grade and 10.2 ± 0.5 years for the 4th grade) from Czech primary schools. Participants were stratified into two groups: intact children (IC; 50 in the 3rd grade, 64 in the 4th grade) and those with developmental dysgraphia (DD; 59 in the 3rd grade, 96 in the 4th grade), as diagnosed by a special education needs teacher who followed a comprehensive Czech standardized battery (including achievement tests for school skills). Regarding gender distribution, 34 boys and 16 girls attended the 3rd grade in the IC group, while 50 boys and 14 girls attended the 4th grade in the IC group. In the DD group, 38 boys and 21 girls attended the 3rd grade, and 75 boys and 21 girls attended the 4th grade. No significant differences in age or gender were observed between the groups in either grade.

During data acquisition, children were instructed to complete two Archimedean spirals (7 cm and 14 cm wide, respectively) on a Wacom Cintiq 16 (DTK1660K0B) display tablet as quickly as possible. Each graphomotor element was printed on a separate sheet of paper. Before beginning the acquisition, the children were given an opportunity to familiarize themselves with the tablet by engaging in free-drawing activities, such as drawing a random picture.

The parents of all children participating in this study provided informed consent, which was approved by the Ethics Committee of the Institute of Psychology at the Czech Academy of Sciences. The study adhered to the Ethical Principles of Psychologists and Code of Conduct as outlined by the American Psychological Association [10] throughout its duration.

B. Feature Extraction

To quantify the regularity of the spirals and assess drawing fluency, we extracted the following commonly used features (although primarily in the context of Parkinson's disease dysgraphia) from the recorded time series [11], [12]: the relative number of interruptions (i.e., the number of pen elevations normalized by duration), the degree of spiral drawing severity, first-order smoothness of the spiral, second-order smoothness of the spiral, the spiral precision index, spiral tightness, variability in spiral width, and the relative number of changes in the velocity profile (normalized by duration).

Additionally, to further examine kinematic abilities and analyze finer details in handwriting kinematics, we employed fractional order derivatives (FDs). Fractional calculus (FC) represents a generalization of classical differential calculus and allows us to analyze signals with temporal memory effects and non-integer orders of differentiation. By utilizing FDs, we aim to capture subtle nuances in handwriting dynamics that may not be apparent in traditional integer-order derivatives. In our previous works, we have explored the use of FDs for analyzing handwriting in neurodegenerative disorders [13] and children with DD [14], [15], demonstrating their potential to capture subtle nuances in motor control and coordination. For this study, we utilized the Caputo FD, defined as [16]:

$${}^C D^\alpha y(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t (t-\tau)^{n-\alpha-1} y^n(t) dt, \quad (1)$$

where ${}^C D^\alpha y(t)$ denotes the Caputo derivatives of order α of the function $y(t)$, Γ is the gamma function, and $n-1 < \alpha \leq n$, $n \in \mathbb{N}$, $t > 0$.

FD kinematic features were calculated for α orders 0.1, 0.5, and 0.9. Features were computed from on-surface movement only and for each separate stroke. Subsequently, we merged the stroke features into a single representation by calculating the median. Features were computed separately from the trajectory and vertical and horizontal movements, resulting in 9 FD features per task. Additionally, we computed standard velocity features (first-order derivative) from the trajectory and horizontal and vertical movements for comparison.

C. Statistical Analysis and Machine Learning

Before conducting the statistical analysis, we considered grade and gender as confounding factors and removed their effects using linear regression [17]. To examine the discriminatory power of the features in each task separately, we employed the Mann-Whitney U test. In addition, we calculated Spearman's correlation with the diagnosis (IC/DD) to determine whether high or low values of a feature were significantly associated with DD. To control for multiple comparisons, we applied a false discovery rate (FDR) correction. To evaluate the effects of diagnosis and scale (large vs. small spiral) on performance, we conducted a two-way analysis of variance (ANOVA). The model included two independent variables: diagnosis and task, along with their interaction. For the ANOVA, features that did not follow a normal distribution (as assessed by the Shapiro-Wilk test) were subsequently transformed using the Box-Cox method.

Finally, to assess the potential of both tasks in a decision-support system, we conducted a classification analysis using the XGBoost algorithm within a 10-fold cross-validation framework with five repetitions. A Bayesian optimization strategy was employed to fine-tune the hyperparameters, with the Matthews Correlation Coefficient (MCC) serving as the primary optimization metric. The model's performance was evaluated using balanced accuracy (BACC), sensitivity (SEN), specificity (SPE), and MCC. Additionally, to gain insight into the contribution of particular features, we explored feature importances.

III. RESULTS

Results of the exploratory statistical analysis are given in Table I. The table includes only features that significantly differed between the IC and CC groups, as assessed by the Mann-Whitney U test, in at least one task. All significant features are velocity-based. For the big spiral, we observed a significant difference in the number of changes in the velocity profile and vertical velocity; however, these results did not pass the FDR correction. Regarding the small spiral, we identified significant differences in vertical and horizontal velocity, as well as in the number of changes in the velocity profile – all of which remained significant after FDR correction. In both tasks, children with DD exhibited increased velocity and a higher number of changes in the velocity profile.

TABLE I. SELECTED RESULTS OF THE EXPLORATORY STATISTICAL ANALYSIS

Big spiral					
Feature	ρ (IC/DD)	p (IC/DD)	adj p (IC/DD)	p (MWU)	adj p (MWU)
relative number of changes in the velocity profile	0.13	0.0306	0.2218	0.0310	0.2220
vertical velocity (median, $\alpha = 0.9$)	0.13	0.0401	0.2218	0.0404	0.2220
vertical velocity (median, $\alpha = 1.0$)	0.14	0.0183	0.2218	0.0186	0.2220
horizontal velocity (median, $\alpha = 0.1$)	0.05	0.3981	0.5307	0.3975	0.5300
horizontal velocity (median, $\alpha = 0.5$)	0.10	0.0998	0.2218	0.0999	0.2220
horizontal velocity (median, $\alpha = 0.9$)	0.05	0.4400	0.5491	0.4394	0.5484
Small spiral					
Feature	ρ (IC/DD)	p (IC/DD)	adj p (IC/DD)	p (MWU)	adj p (MWU)
relative number of changes in the velocity profile	0.21	0.0006	0.0042	0.0007	0.0047
vertical velocity (median, $\alpha = 0.9$)	0.16	0.0103	0.0411	0.0105	0.0422
vertical velocity (median, $\alpha = 1.0$)	0.06	0.2990	0.4663	0.2985	0.4655
horizontal velocity (median, $\alpha = 0.1$)	0.21	0.0005	0.0042	0.0006	0.0047
horizontal velocity (median, $\alpha = 0.5$)	0.23	0.0002	0.0031	0.0002	0.0037
horizontal velocity (median, $\alpha = 0.9$)	0.18	0.0026	0.0132	0.0028	0.0140

* ρ (IC/DD) – Spearman’s correlation coefficient with the diagnosis; p (IC/DD) – p-value of Spearman’s correlation with the diagnosis; adj p (IC/DD) – adjusted p-value of Spearman’s correlation with the diagnosis; p (MWU) – p-value of the Mann-Whitney U test; adj p (MWU) – adjusted p-value of the Mann-Whitney U test

The two-way ANOVA revealed significant main effects of both diagnosis and scale on several drawing features. Children with DD exhibited significantly greater degree of spiral drawing severity ($p = 0.0038$), lower tightness of the spiral ($p = 0.0310$), lower spiral precision ($p = 0.0012$), a higher number of changes in the velocity profile ($p = 0.0038$), and increased horizontal velocity ($p = 0.0473$ for $\alpha = 0.9$). The scale also had a significant impact, with degree of spiral drawing severity ($p = 0.0392$), first-order smoothness of the spiral ($p = 0.0359$), and velocity differing between the big and small spiral tasks. This difference was particularly pronounced in vertical velocity (e.g., $p < 0.0001$ for $\alpha = 0.9$), where lower values were observed in the small spiral. No significant interaction effects between diagnosis and scale were found.

Regarding the classification analysis, the model trained on features extracted from the small spiral demonstrated superior performance, achieving a BACC of 0.61 ± 0.09 , with SEN of 0.77 ± 0.08 , SPE of 0.45 ± 0.16 , and MCC of 0.23 ± 0.19 . In contrast, the model based on the large spiral obtained a BACC of 0.53 ± 0.08 , with SEN of 0.71 ± 0.10 , SPE of 0.35 ± 0.13 , and MCC of 0.07 ± 0.17 . Feature importance analysis revealed that the most relevant features were related to FD-based velocity metrics, with vertical movement features being more represented in the first model (large spiral), while a combination of both vertical and horizontal velocity-based features was observed in the second model (small spiral). Additionally, the spiral precision index and the relative number of changes in the velocity profile contributed significantly to the classification.

IV. DISCUSSION

Children with DD drew spirals faster and with more frequent velocity changes than controls but showed worse quality (greater distortion). This suggests that speed gains did not improve performance. Prior studies similarly report disfluent, effortful strokes in dysgraphia, where increased speed most likely reflects poor motor automation rather than fluency [2], [6]. This highlights a core graphomotor impairment: faster movement comes at the cost of control.

To further explore this, we performed Spearman’s correlation between median vertical velocity ($\alpha = 0.9$; significant in both tasks) and spiral quality. Among typically developing children, higher speeds (especially on the large spiral) correlated with worse quality: greater spiral drawing severity ($\rho = 0.34$, $p = 0.0013$) and reduced tightness ($\rho = -0.32$, $p = 0.0013$), reflecting a speed–accuracy trade-off. However, children with DD showed no strong speed–quality correlation on the large spiral, with consistently poor performance. Yet, in the smaller, more demanding spiral, increased speed was associated with greater spiral drawing severity ($\rho = 0.25$, $p = 0.0087$), suggesting difficulty in regulating speed for accuracy, particularly in fine movements.

Spiral-based classification showed moderate accuracy, with high sensitivity (77%) but low specificity (45%). While this supports its use as a screening tool, the risk of false positives must be considered. Prior studies also report higher sensitivity than specificity in early DD detection [8], suggesting that graphomotor tests can help identify at-risk children for further assessment [18]. Although DD does not always involve generalized fine motor deficits, our findings support that specific motor control challenges can emerge in precision-based tasks such as spiral drawing.

The small spiral (particularly in relation to vertical movement) was especially challenging for children with DD, reinforcing the idea that finer motor coordination is required for small movement amplitudes. Vertical movement engages more muscles and requires greater control, making accuracy more difficult [15], [19].

FD-based features outperformed traditional kinematics in distinguishing children with DD from controls. Fractional-order derivatives capture “memory” effects in motion and detect subtle irregularities missed by integer-order metrics. FD-based velocity measures were more sensitive to dysgraphic anomalies, improving classification. Similar studies report that FD-derived features enhance dysgraphia detection, offering a superior method for quantifying subtle motor impairments [14], [15].

V. CONCLUSION

This study investigated the impact of speed and scale on spiral drawing in children with DD. Our findings support the hypothesis that children with DD exhibit greater deficits in fluency and motor control, particularly when drawing small spirals, which require finer motor coordination. Compared to typically developing peers, children with DD produced spirals with more frequent velocity changes and increased drawing speed, but at the cost of reduced precision. These results highlight a fundamental motor impairment in DD, where increased speed does not equate to improved performance but rather reflects reduced control and automation.

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