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Short Report

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Mechanical Assistive Writing Tool for Students with Developmental Disabilities

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Abstract

Handwriting difficulties are prevalent among students with developmental and neurodevelopmental disabilities, often resulting from compromised visual-motor integration and spatial organization deficits. This study evaluated the classroom-based effectiveness of a structured mechanical assistive writing tool in improving handwriting performance among exceptional learners. A pre-experimental design was conducted with 58 students exhibiting handwriting impairments across diverse diagnostic profiles, including intellectual disability, autism spectrum disorder, and specific learning disability. The intervention comprised 20 structured handwriting sessions administered five times weekly. Handwriting performance was evaluated across five spatial domains (letter alignment, letter spacing, word spacing, letter size consistency, and overall legibility) using an analytical rubric scored by independent raters. Inferential analyses revealed a statistically significant increase in composite handwriting scores from pre-test ($M = 42.57, SD = 10.22$) to post-test ($M = 66.29, SD = 20.73$), $t(57) = -9.20, p < .001$ (Cohen's $d = 1.21$), with non-parametric verification confirming robust gains across all participants (Wilcoxon $Z = -6.62, p < .001, r = .87$). The largest improvements occurred in letter size consistency and horizontal alignment. While baseline proficiency was uniformly low, variance in gain scores reflected differing cognitive capacities and motor thresholds, differentiating rapid procedural internalizers from students requiring sustained physical scaffolding. These findings substantiate that the GGR provides an effective, low-tech mechanical scaffold that externalizes spatial constraints, reduces cognitive load, and enhances handwriting legibility in special education settings.

Keywords: Assistive technology; Handwriting skills; Visual-motor integration; Special education; Spatial regulation; Fine motor skills.

Introduction

Handwriting remains a foundational academic tool underpinning written communication, cognitive organization, and formal curriculum participation [1], [2]. In elementary and special education environments, proficient handwriting demands the harmonious orchestration of fine-motor coordination, visual-spatial perception,

kinesthetic feedback, and motor planning [3], [4]. When any of these foundational processes are compromised, students frequently encounter persistent barriers to academic productivity, task completion, and self-efficacy [5], [6] .

Students with diverse developmental and neurodevelopmental disabilities, including intellectual disabilities, autism spectrum disorder (ASD), and specific learning disabilities (SLD) exhibit disproportionately high rates of spatial handwriting impairments [7], [8]. Clinically, these manifestations include erratic inter-letter spacing, fluctuating letter dimensions, drifting line alignment, overlapping graphemes, and overall diminished legibility [9], [10]. Conventional classroom-based remediation predominantly relies on repetitive rote copying and verbal feedback. However, these traditional techniques often fail to address the underlying visual-motor integration constraints and mechanical instability experienced by exceptional learners [11], [12] .

Recent empirical inquiries underscore the necessity of external structured spatial scaffolds to guide motor trajectory and stabilize written output [13], [14] . While purely visual supports (e.g., color-coded lines, raised-line paper) provide perceptual markers, they lack tangible physical boundaries capable of arresting erratic fine-motor drift [3], [12]. Low-tech mechanical assistive devices, conversely, introduce physical constraints that mechanically limit spatial variance, stabilize the writing medium, and reduce extraneous cognitive demands during letter formation [15], [16] .

To operationalize this principle, the Graphia Guide Ruler (GGR) was previously developed and prototyped as a dedicated, low-cost assistive writing scaffold. The device combines a slotted baseline frame, an integrated sliding spacer, and a stabilizing anchor plate to physically constrain letter height, alignment, and inter-character intervals. While earlier developmental stages established the functional feasibility and mechanical ergonomics of the GGR, empirical validation regarding its classroom-based intervention efficacy among exceptional learners has not yet been documented.

Therefore, the present study addresses this empirical gap by evaluating the effectiveness of the GGR within an authentic special education classroom setting. Specifically, this study addressed the following research questions:

1. Does structured intervention with the GGR yield statistically significant improvements in overall handwriting performance among students with diverse developmental disabilities?
2. To what extent does the GGR affect specific spatial components of handwriting, including alignment, spacing, sizing, and legibility?

Method

Research Design

This study employed a pre-experimental single-group pre-test–post-test design ($O_1 \rightarrow X \rightarrow O_2$). Given the clinical heterogeneity and limited enrollment typical of special

education settings, a single-group design with rigorous repeated-session protocols was adopted to ensure ecological validity within authentic classroom routines. This study was conducted at 3 special schools and 5 inclusive schools in Malang, East Java, Indonesia. Ethical clearance was obtained from the institutional ethics committee of Universitas Negeri Malang (Approval Protocol No. 17.6.58/UN32.14/PB/2025), and written informed consent was secured from parents or legal guardians.

A purposive sample of 58 students in the study was selected based on the following inclusion criteria: (a) enrolled in formal special education, (b) identified as exhibiting functional handwriting impairments (score < 55 on baseline screening), (c) possession of functional upper-limb motor capability to hold a writing implement, and (d) ability to follow two-step verbal or visual instructions. The demographic and diagnostic composition is summarized in Table 1.

Table 1. Participant Demographic and Diagnostic Characteristics ($N = 58$)

Variable	**Classification**	**n**	**Percentage (%)**
Gender	Male	33	56.8%
	Female	25	43.2%
Primary Disability Profile	Intellectual Disability	20	34.5%
	Autism Spectrum Disorder (ASD)	12	20.7%
	Specific Learning Disability	26	44.8%
Hand Dominance	Right-handed	54	93.1%
	Left-handed	4	6.9%

Procedure

The GGR (Model GGR-v2; Special Education Laboratory UM, Malang, Indonesia) is fabricated from high-density, lightweight polylactic acid polymer. It consists of: (a) a slotted horizontal frame (aperture height: 15 mm) establishing upper and lower mechanical limits, (b) a dynamic sliding spacer (width: 8 mm) moving smoothly along the longitudinal axis to govern spacing, and (c) an anti-slip baseboard to immobilize writing paper against lateral shear (See Fig.1).

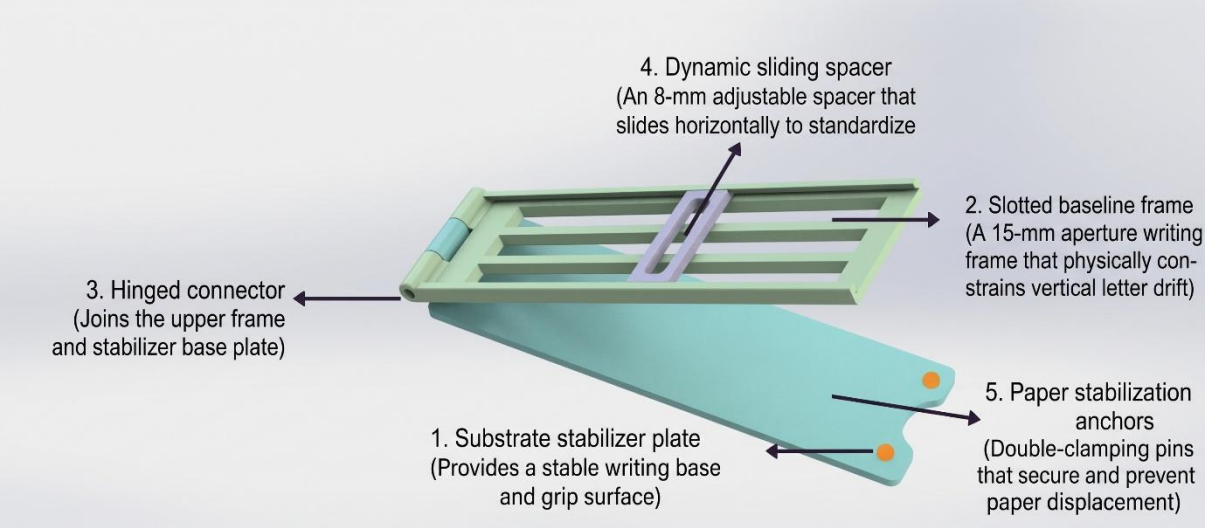


Figure 1. Mechanical anatomy and functional components of GGR

Handwriting performance was quantified using a standardized, 5-dimension analytical handwriting rubric adapted from established pediatric assessment frameworks (Stuart et al., 2024):

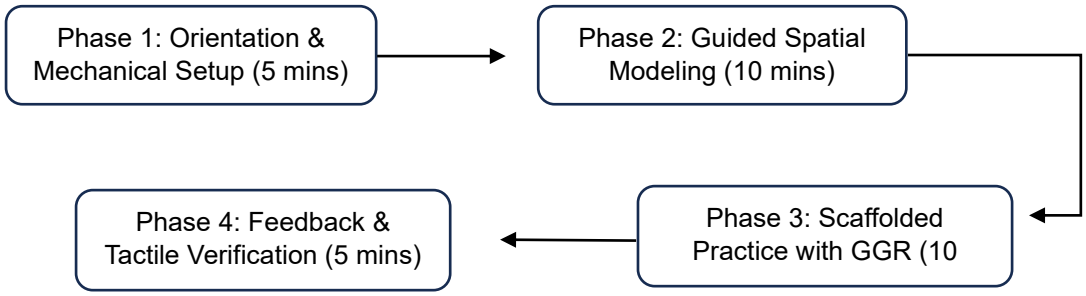
1. Letter Alignment (0–20): Adherence to the baseline without erratic vertical drifting.
2. Letter Spacing (0–20): Consistency of gaps between adjacent graphemes within words.
3. Word Spacing (0–20): Regularity of spatial pauses separating individual words.
4. Letter Size Consistency (0–20): Proportional uniformity of ascenders, descenders, and short letters.
5. Overall Legibility (0–20): Readability, stroke closure, and absence of character distortion.

The composite score ranged from 0 to 100, where higher scores reflect superior handwriting proficiency.

To eliminate scoring bias, all pre-test and post-test handwriting samples were anonymized, randomized, and independently scored by two trained special educators blinded to participant identity and test timing (pre- vs. post-test). Inter-rater reliability was calculated using the Two-Way Mixed Intraclass Correlation Coefficient (ICC), yielding an excellent agreement of ICC $= .89$ (95% CI $[.81, .94]$). Consensus scores were utilized for statistical analysis. Both pre-test and post-test assessments were conducted under unassisted baseline conditions (free-hand writing without the GGR apparatus) to evaluate actual motor skill learning and retention.

Intervention Protocol

The intervention spanned four consecutive weeks, comprising 20 structured sessions (5 sessions/week, 30 minutes/session). Each session followed a 4-phase structured pedagogical format:



Statistical Analysis

Data were analyzed using descriptive and inferential statistical procedures. The distribution of pre-test, post-test, and gain scores was assessed for normality using the Shapiro–Wilk test. Because both pre-test and post-test distributions significantly deviated from normality ($p < .05$), a dual analytical approach was executed to ensure analytical rigor: parametric paired-samples t-tests (reporting mean differences, 95% confidence intervals, and Cohen's d) and non-parametric Wilcoxon signed-rank tests (reporting Z-statistics, asymptotic p-values, and effect size $r = \frac{|Z|}{\sqrt{N}}$). In addition to total handwriting scores, separate sub-analyses were conducted across all five rubric dimensions: letter alignment, letter spacing, word spacing, letter size consistency, and overall legibility.

Result

Descriptive Statistics and Distribution Characteristics

Descriptive parameters for handwriting performance before and after the 20-session intervention using the Graphia Guide Ruler (GGR) are presented in Table 2. Prior to the intervention, students exhibited low handwriting proficiency ($M = 42.57, SD = 10.22$, median $= 43.00$, range: $25.00 - 78.00$), marked by pervasive spatial irregularities. Following the intervention, the mean handwriting score rose substantially to 66.29 ($SD = 20.73$, median $= 58.00$, range: $35.00 - 98.00$), reflecting an average gain of $+23.72$ points ($SD = 19.64$).

Table 2. Descriptive Statistics of Handwriting Performance ($N = 58$)

Assessment Phase	Mean (M)	Std. Deviation (SD)	Median	IQR	Min	Max
Pre-test	42.57	10.22	43.00	11.75	25.00	78.00
Post-test	66.29	20.73	58.00	38.75	35.00	98.00
Gain Score (Δ)	23.72	19.64	14.00	35.50	2.00	64.00

Normality evaluation using the Shapiro–Wilk test (Table 3) confirmed that the composite pre-test scores ($W = .936, p = .004$), post-test scores ($W = .868, p < .001$), and difference scores ($W = .838, p < .001$) violated the assumption of normal distribution. Consequently, non-parametric analyses were prioritized alongside parametric comparisons.

Table 3. Normality Test Results (Shapiro–Wilk Test)

Variable	Statistic (W)	df	Sig. (p)	Distribution
Pre-test Total	.936	58	.004	Non-normal
Post-test Total	.868	58	$< .001$	Non-normal
Difference Score (Post – Pre)	.838	58	$< .001$	Non-normal

Inferential Analysis of Overall Handwriting Improvement

The paired-samples t-test indicated a statistically significant improvement in overall handwriting scores from baseline to post-intervention, $t(57) = -9.200, p < .001$ (Table 4). The mean difference of -23.72 (95% CI $[-28.89, -18.56]$) represented a large intervention magnitude, with Cohen's $d = 1.21$.

Table 4. Paired-Samples t-Test on Overall Composite Scores ($N = 58$)

Comparison	Mean Diff.	Std. Error	95% CI Lower	95% CI Upper	t	df	p (2-tailed)	Cohen's d
Pre vs. Post	-23.72	2.58	-28.89	-18.56	-9.200	57	$< .001$	1.21

Component-Level Handwriting Performance Breakdown

To determine the specific spatial dimensions driving overall improvement, changes across the five rubric indicators were examined independently (Table 5). Statistically significant gains were detected across all five domains ($p < .001$ on both parametric and non-parametric tests). The largest absolute mean increase occurred in Letter Size Consistency ($+5.07$ points, Cohen's $d = 1.14, r = .82$) and Letter Alignment ($+4.93$ points, Cohen's $d = 1.19, r = .82$), aligning directly with the primary physical constraints imposed by the GGR's slotted frames. Substantial improvements were also recorded in Letter Spacing ($+4.59$ points, $r = .82$), Word Spacing ($+4.59$ points, $r = .83$), and Overall Legibility ($+4.55$ points, $r = .81$).

Table 5. Breakdown of Performance Across Rubric Dimensions (Scale: 0–20 per indicator; $N = 58$)

Rubric Dimension	Pre-test M(SD)	Post-test M(SD)	Gain M(SD)	t(57)	p-value (t-test)	Cohen's d	Wilcoxon Z	p-value (Wilcoxon)	Effect Size (r)
A. Letter Alignment	8.71 (2.44)	13.64 (4.25)	4.93 (4.15)	9.049	$< .001$	1.19	-6.280	$< .001$	.82
B. Letter Spacing	8.76 (2.39)	13.34 (4.46)	4.59 (3.79)	9.208	$< .001$	1.21	-6.225	$< .001$	.82
C. Word Spacing	8.34 (2.28)	12.93 (4.35)	4.59 (3.91)	8.940	$< .001$	1.17	-6.283	$< .001$	.83
D. Letter Size Consistency	8.34 (2.62)	13.41 (4.34)	5.07 (4.43)	8.718	$< .001$	1.14	-6.222	$< .001$	.82
E. Overall Legibility	8.41 (2.34)	12.97 (4.55)	4.55 (4.26)	8.145	$< .001$	1.07	-6.173	$< .001$	.81

Discussion

The present study evaluated the intervention efficacy of the Graphia Guide Ruler (GGR) across 58 students presenting with diverse developmental disabilities. Overall, the findings demonstrated statistically significant and substantial gains in composite handwriting legibility and spatial organization ($M_{\text{pre}} = 42.57$ vs. $M_{\text{post}} = 66.29, p < .001, r = .87$). Positive trajectory was documented across every single participant without negative ranks, affirming that external mechanical structuring serves as a universally viable compensatory scaffold in special education environments.

A detailed examination across the five rubric dimensions revealed that the most pronounced enhancements occurred in letter size consistency ($+5.07$ points) and letter alignment ($+4.93$ points). These specific gains map directly onto the primary affordances of the GGR apparatus. The slotted physical frame establishes non-negotiable upper and lower baselines, mechanically converting unbounded 2D paper space into a constrained, single-dimensional trajectory. Consequently, the ruler's

physical boundary directly arrested vertical drifting and disproportionate ascender/descender extensions, frequent manifestations of impaired proprioceptive and kinesthetic feedback. Concurrently, the sliding spacer transformed the abstract spatial construct of uniform inter-letter and inter-word intervals into an overt, tactile-motor maneuver, which accounted for substantial gains in horizontal spacing ($+4.59$ points).

The efficacy of the GGR can be understood through its direct tactile-mechanical feedback. Unlike conventional instructional interventions that rely heavily on auditory prompts or purely visual guides (e.g., standard ruled lines), the GGR physically restricts letter deviation via its rigid slotted frame (Koul et al., 2024). When writing within the constrained lanes, a student's pen strokes receive immediate somatic feedback whenever vertical or lateral drift begins. This boundary regulation stabilizes motor output, thereby promoting the development of consistent motor programs (Alhaddad et al., 2025; Suggate et al., 2023).

Furthermore, the sliding spacer successfully externalizes the abstract concept of uniform spacing. For students with intellectual disabilities or ASD, calculating spatial intervals between letters and words is a frequent source of cognitive friction (Le Pong et al., 2025; Re et al., 2023). Mechanically sliding the spacer converts an abstract spatial judgment into a concrete, reproducible motor behavior. This directly decreases extraneous cognitive load, enabling learners to dedicate attentional resources toward letter formation and stroke closure (Cerni & Job, 2024; Truxius et al., 2024).

The observed improvements can be fundamentally explained through the lens of Motor Learning Theory and Cognitive Load Theory [17], [18]. Producing legible handwriting requires the simultaneous coordination of visual-spatial perception, motor planning, fine-motor pinch force, and continuous error-monitoring. In neurodivergent learners, the neural pathways governing visual-motor integration often require high attentional investment simply to keep writing strokes aligned on conventional ruled paper. When learners must allocate extensive working memory resources to judging spatial coordinates and boundary limits, fewer cognitive resources remain available for orthographic retrieval, stroke sequence execution, and letter formation.

The GGR alleviates this friction by externalizing spatial regulation. By providing tangible, somatic boundaries, the apparatus mechanically offloads spatial computation from the learner’s central executive system. Rather than relying strictly on visual cues, which are frequently compromised in children with developmental coordination difficulties or sensory processing differences, the student receives instantaneous haptic and mechanical feedback whenever a writing instrument contacts the guide’s perimeter. This immediate somatosensory constraint reduces motor variability, lowers extraneous cognitive load, and stabilizes the formation of generalized motor programs.

Despite significant gains across the entire sample, inferential variance testing revealed pronounced heterogeneity in the magnitude of improvement (Levene’s test on gain scores: $F = 12.365, p < .001$). While baseline performance was uniformly low across

the cohort ($M = 42.57, p = .283$), post-intervention gains clustered into two distinct response trajectories: a subset of participants achieved extensive skill acquisition ($M_{\text{gain}} \approx 45.91$), whereas another subset demonstrated moderate, incremental gains ($M_{\text{gain}} \approx 9.14$). Crucially, this variance reflects fundamental individual differences in baseline neurodevelopmental profiles rather than a failure of the mechanical intervention.

The acquisition of fluent handwriting from mechanical scaffolds requires a functional threshold of executive functioning, specifically working memory, inhibitory control, and procedural sequencing. Students with milder cognitive delays or specific learning difficulties (e.g., dysgraphia) typically possess intact procedural internalization. For these learners, the GGR operated as an accelerative cognitive scaffold. Once spatial parameters were made concrete by the tool, they rapidly abstracted the spatial rules and transferred them to unassisted writing conditions. Conversely, participants with moderate-to-severe intellectual disabilities experience steeper challenges in procedural schema formation. While the mechanical frame successfully guided their hand during guided practice, the internalization of these spatial bounds into unassisted writing was more gradual, resulting in modest yet clinically meaningful functional increments.

Handwriting difficulties in special populations rarely represent a homogenous impairment. In students whose primary barrier is spatial disorientation (e.g., directional confusion, spatial neglect, or difficulty gauging margins), the GGR's slotted rails and sliding spacer provided an immediate, highly effective compensatory fix. However, in participants presenting with co-occurring intrinsic fine-motor neuromotor deficits such as severe kinetic tremors, abnormal palmar grasp, joint laxity, or spastic muscular hypertonia, mechanical guides alone cannot fully remediate intrinsic grip instability or distal finger control. For this subgroup, physical boundaries effectively stabilize line drift, but character distortion and stroke closure remain constrained by fundamental motor execution thresholds.

The standardized 20-session dosage (approximately 10 hours of cumulative practice) proved sufficient for rapid responders to complete the progression from associative motor practice to autonomous execution. However, motor learning in learners with complex neurodevelopmental profiles adheres to extended associative trajectories. For students showing incremental gains, 20 sessions represent an initial acquisition phase rather than a complete internalization cycle. Such learners likely require prolonged physical scaffolding before mechanical withdrawal can occur without partial regression. Beyond improving spatial consistency, the GGR's structured mechanical environment may also reduce cognitive load during writing tasks. Students who struggle with handwriting often expend significant cognitive effort on spatial planning, including decisions about letter placement and alignment. By externalizing spatial regulation through mechanical constraints, the GGR reduces the need for continuous spatial decision-making, allowing students to allocate more cognitive resources to motor execution and letter formation (Alhaddad et al., 2025; Cerni & Job, 2024). This

reduction in cognitive load may contribute to improved writing fluency and task engagement. Intensive and repeated practice has been shown to strengthen motor learning and improve skill acquisition in children with developmental challenges [21], [22]. The structured and repetitive nature of the intervention likely facilitated the consolidation of motor memory, leading to more consistent handwriting performance over time.

Study Limitations and Future Directions

Several methodological constraints should be noted. Although expanding the sample to 58 participants provided robust non-parametric statistical power, the research design lacked an unassisted parallel control group, which limits definitive causal isolation from general maturational influences. Additionally, neurocognitive indices (e.g., standardized IQ, formal visual-motor integration scores via Beery VMI) were not individually correlated against gain scores, precluding formal quantitative moderation modeling.

Future research should implement randomized controlled trials (RCTs) or single-case experimental designs (SCED) incorporating standardized baseline cognitive and visual-motor battery testing. This will allow researchers to mathematically quantify the exact predictive thresholds (e.g., baseline VMI percentile or working memory capacity) that govern whether a child requires short-term transitional scaffolding or permanent mechanical writing accommodations.

Implications for Special Education Practice

These empirical findings provide an essential practical foundation for special educators, occupational therapists, and assistive technology practitioners in designing adaptive writing interventions. The use of the Graphia Guide Ruler (GGR) has proven effective in restoring spatial layout, addressing baseline drift, and standardizing character spacing. However, for learners with more complex fine-motor deficits, this mechanical device should be ergonomically integrated with tools such as pencil grips, wrist stabilization, or adjustments to sitting posture to simultaneously optimize distal motor control. Furthermore, the schedule for phasing out mechanical support cannot be applied uniformly. Rather, it must be tailored to each child’s individual cognitive capacity and motor readiness. Learners with mild learning disabilities may be well-positioned to transition to standard paper without assistive tools following a cycle of intensive intervention, whereas children with moderate intellectual disabilities may require the GGR as a long-term physical accommodation in the classroom. To accelerate the consolidation of spatial motor memory among a diverse population of students with disabilities, it is also recommended that educators combine the physical boundaries provided by the GGR with multisensory stimulation, such as tactile tracing and self-directed verbal instruction strategies during the writing process.

Conculsion

The Graphia Guide Ruler (GGR) demonstrates high efficacy as a low-cost, classroom-deployable mechanical assistive tool for remediating spatial handwriting difficulties in children with developmental disabilities. By physically regulating alignment, standardizing spacing through a dynamic sliding element, and stabilizing paper orientation, the GGR effectively alleviates spatial cognitive load and fosters consistent motor pattern acquisition. Its integration into daily special education routines offers teachers an accessible, evidence-based instructional scaffold.

Data availability

The author confirms that all data generated or analysed during this study are included in this published article (supplementary file). Furthermore, primary and secondary sources and data supporting the findings of this study were all publicly available at the time of submission.

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DECLARATIONS

Ethics approval

The study protocol was reviewed and approved by the Institutional Ethics Committee of Universitas Negeri Malang (Approval Protocol No. 17.6.58/UN32.14/PB/2025) and conducted in strict accordance with the ethical standards of the Declaration of Helsinki.

Consent to participate

Informed consent was obtained verbally from the parents or legal guardians of all participating students prior to the commencement of the study, accompanied by verbal assent from the students. Written consent was waived in this educational intervention setting as participation was entirely voluntary, conducted within routine academic hours, and carried out exclusively for educational enrichment purposes without invasive procedures. The objectives, classroom activities, and voluntary nature of participation were thoroughly explained, and parents/guardians were assured that participation would not affect the students' regular academic status or access to educational services.

Consent to publish

Not applicable

Clinical trial registration

Clinical trial number: Not applicable.

Refferrences

[1] A. S. S. Lee, L. W. Lee, H. M. Low, and S. C. Ooi, “Revisiting handwriting fundamentals through an interdisciplinary framework,” *Malays. J. Med. Sci.*, vol. 29, no. 1, p. 18, 2022.

[2] P. Raghuram *et al.*, “A descriptive analysis of occupational therapy approaches to enhance handwriting skills in primary school students,” *J. Occup. Ther. Sch. Early Interv.*, vol. 19, no. 1, pp. 116–128, 2026.

[3] L. Bray, C. Skubik-Peplaski, and K. B. Ackerman, “A systematic review of the effectiveness of interventions to improve handwriting and spelling in children with specific learning disabilities,” *J. Occup. Ther. Sch. Early Interv.*, vol. 14, no. 4, pp. 437–465, 2021.

[4] M. B. H. Mohamed and B. A. O’Brien, “Defining the relationship between fine motor visual-spatial integration and reading and spelling,” *Read. Writ.*, vol. 35, no. 4, pp. 877–898, 2022.

[5] T. Cerni and R. Job, “Spelling processing during handwriting and typing and the role of reading and visual-motor skills when typing is less practiced than handwriting: T. Cerni, R. Job,” *Read. Writ.*, vol. 37, no. 1, pp. 205–237, 2024.

[6] L. Truxius, M. N. Maurer, J. Sägesser Wyss, and C. M. Roebers, “The internal structure of handwriting proficiency in beginning writers,” *PLoS One*, vol. 19, no. 1, p. e0296096, 2024.

[7] J. Alston and J. dec’d Taylor, *Handwriting: Theory, research and practice*. Taylor & Francis, 2024.

[8] A. M. Re, F. De Vita, C. Cornoldi, and S. Schmidt, “Copy skills and writing abilities in children with and without specific learning disabilities,” *J. Learn. Disabil.*, vol. 56, no. 5, pp. 410–420, 2023.

[9] M. Kadar, F. Wan Yunus, E. Tan, S. C. Chai, N. A. Razaob@ Razab, and D. H. Mohamat Kasim, “A systematic review of occupational therapy intervention for handwriting skills in 4–6 year old children,” *Aust. Occup. Ther. J.*, vol. 67, no. 1, pp. 3–12, 2020.

[10] N. Stuart, S. Zoia, M. Biancotto, and A. L. Barnett, “The Handwriting Legibility Scale: A language and age extension for students with and without specific learning difficulties,” *J. Mot. Learn. Dev.*, vol. 12, no. 3, pp. 610–634, 2024.

[11] N. Bonneton-Botté, L. Miramand, R. Bailly, and C. Pons, “Teaching and rehabilitation of handwriting for children in the digital age: Issues and challenges,” *Children*, vol. 10, no. 7, p. 1096, 2023.

[12] G. Lemire, T. Laliberté, K. Turcot, V. H. Flamand, and A. Campeau-Lecours, “Preliminary development and evaluation of a mechanical handwriting assistive device to support individuals with movement disorders,” *Frontiers in Rehabilitation Sciences*, vol. 5, p. 1418534, 2025.

[13] T.-H. Howe, J. Le Pong, Z.-C. Weng, H.-L. Chen, and T.-N. Wang, “A Geometric-Based Handwriting Intervention (GBHI) for Chinese Handwriting: Development, Feasibility, and Pilot Findings,” *Hong Kong Journal of Occupational Therapy*, p. 15691861251357339, 2025.

[14] S. Murnani, K. Hashitsume, and T. Igasaki, “Handwriting Difficulties: A Review of Recent Advances in the Identification and Intervention,” *IEEE Access*, 2025.

[15] P. Koul, S. Morghade, R. K. Kovela, and S. B. Rewatkar, “Efficacy of assistive technology on improvement of handwriting skills in learning disabilities and developmental coordination disorder: A literature review,” in *AIP Conference Proceedings*, AIP Publishing LLC, 2024, p. 100014.

[16] A. J. Taylor and J. Smith, “Assistive Technology for Learning to Write and Writing to Learn,” in *An Evidence-Based Guide to Assistive Technology*, 1st ed., New York: Routledge, 2026, ch. 1, pp. 120–132.

[17] J. Sweller, “The Development of Cognitive Load Theory: Replication Crises and Incorporation of Other Theories Can Lead to Theory Expansion,” *Educ. Psychol. Rev.*, vol. 35, no. 4, p. 95, 2023, doi: 10.1007/s10648-023-09817-2.

[18] P. S. Beach, M. Perreault, A. Brian, and D. H. Collier, *Motor learning and development*. Human kinetics, 2024.

[19] G. Alhaddad, J. Danna, M. Dione, and M. Longcamp, “The influence of fine motor skills and executive functions on automatized handwriting,” *Cogn. Neuropsychol.*, pp. 1–13, 2025.

[20] T. Cerni and R. Job, “Spelling processing during handwriting and typing and the role of reading and visual-motor skills when typing is less practiced than handwriting,” *Read. Writ.*, vol. 37, no. 1, pp. 205–237, 2024.

[21] M. K. Schneider, C. T. Myers, J. Morgan-Daniel, and O. Shechtman, “A scoping review of grasp and handwriting performance in school-age children,” *Phys. Occup. Ther. Pediatr.*, vol. 43, no. 4, pp. 430–445, 2023.

[22] C. Lopez-Escribano, J. Martin-Babarro, and R. Perez-Lopez, “Promoting handwriting fluency for preschool and elementary-age students: Meta-analysis and meta-synthesis of research from 2000 to 2020,” *Front. Psychol.*, vol. 13, p. 841573, 2022.

Supplementary Files

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- Dataset.xlsx