Does Removing Pen Pressure in Cost-Cutting Pen Designs Matter for Handwritten Learning in Education? A Case Study of Geometry Problem Solving

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Abstract

Digital handwriting is increasingly used in educational settings; however, many classroom styluses omit pen pressure sensitivity due to cost and procurement constraints. While prior work has shown that pen pressure supports written arithmetic, its role in other learning activities remains insufficiently understood. In this study, we investigate how pen pressure–based stroke modulation affects problem-solving performance in digital handwriting, using geometry problems as a case study. We conducted a between-subjects experiment comparing pressure-sensitive and non-pressure-sensitive conditions in tasks requiring spatial reasoning and iterative diagram construction. Although overall accuracy did not differ significantly between conditions, detailed analyses revealed that the absence of pen pressure disproportionately affected lower-performing participants and reduced accuracy in unfamiliar or cognitively demanding problems. In solid geometry tasks, the non-pressure-sensitive condition also resulted in longer completion times. Qualitative analyses further showed that pen pressure enabled effective visual organization and depth representation, whereas its absence led participants to adopt compensatory diagramming strategies, such as relocating annotations outside figures. These findings indicate that omitting pen pressure is not a cognitively neutral design decision. Pen pressure functions as a representational resource that supports exploratory reasoning and visual organization in digital handwriting, with important implications for the design of educational input devices and learning environments.

CCS Concepts

• **Human-centered computing** → **Graphics input devices**; **User studies**; • **Applied computing** → *Interactive learning environments*.

Keywords

Pen Pressure, Digital Handwriting, Handwriting, Geometry Problems, Digital Education

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1 Introduction

Handwriting-capable devices, such as smartphones and tablets, have become increasingly commonplace in educational settings worldwide [11, 23]. As digital handwriting tools are introduced into classrooms, students now have more opportunities to practice writing in digital environments. In Japan, a 2023 survey by the Ministry of Education, Culture, Sports, Science and Technology reported that 99.9% of municipalities nationwide have provided one learning device per student in elementary and junior high schools, ensuring near-universal access to digital learning environments [13]. Similar large-scale initiatives have been reported in other educational systems.

Prior research suggests that handwritten note-taking is more effective for learning than typing on a laptop [5, 9, 14]. However, the impact of replacing traditional paper-and-pencil handwriting with digital handwriting tools remains insufficiently understood, particularly with respect to which design features are critical for supporting effective learning.

One fundamental characteristic of handwriting with paper and pencil is that pen pressure naturally modulates stroke darkness, allowing learners to visually organize information during writing and drawing. To replicate this property in digital environments, pressure-sensitive pens and software have been developed. However, due to budget constraints in many educational settings, pen pressure detection is often omitted from the styluses bundled with tablets, resulting in digital handwriting environments in which

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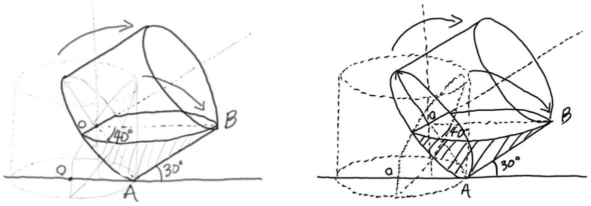

(a) Diagram with stroke darkness modulation

(b) Diagram without stroke darkness modulation

Figure 1: Comparison of diagrams (a) with stroke darkness modulation and (b) without stroke darkness modulation.

stroke appearance is fixed[1]. In Japan, this situation is exemplified by nationwide initiatives to provide each student with a personal digital device [13].

Kobayashi et al. [10] focused on this issue and conducted arithmetic calculation tasks under two conditions, with and without pen pressure. Their results showed that, in arithmetic problems requiring written annotations, such as long-division tasks, performance was lower in the non-pressure-sensitive condition than in the pressure-sensitive condition, and that measurable differences in writing behavior emerged. However, the role of pen pressure in tasks beyond arithmetic calculations remains largely unexplored.

In particular, geometry problem solving involves spatial reasoning and iterative construction, during which learners may rely on variations in stroke darkness to represent uncertainty or intermediate steps (Figure 1). These characteristics make geometry problem solving a suitable testbed for examining the role of pen pressure beyond arithmetic calculations.

In this study, we examine how pen pressure in educational digital handwriting affects problem-solving performance, using geometry problems as a case study. We hypothesize that allowing pen pressure to influence stroke darkness will support more effective problem solving compared to a non-pressure-sensitive condition in which stroke appearance is fixed.

The contributions of this study are summarized as follows:

- **Design Perspective on Pen Pressure Removal**: This study framed the absence of pen pressure in educational digital handwriting as a design and procurement decision rather than a technical limitation, and empirically examined its impact on learning-related problem solving.
- **Boundary Conditions of Pen Pressure Benefits**: Using geometry tasks as a case study, this study showed that the benefits of pen pressure are selective rather than global. In particular, pen pressure was more beneficial in unfamiliar or cognitively demanding tasks that required trial-and-error exploration, spatial reasoning, and visual organization.
- **Behavioral Insights into Compensatory Strategies**: Through qualitative analysis, the study identified adaptive diagramming strategies, such as placing annotations outside figures, that learners employed to compensate for the lack of stroke differentiation. These findings offered actionable insights for the design of adaptive digital handwriting tools that better support diverse problem-solving behaviors.

2 Related Work

2.1 Research on Pen Pressure

Many studies have investigated the relationship between pen pressure and the internal states of writers. Schrader et al. [18] explored how learners' emotions and motivation correlate with handwriting skills during the acquisition of Japanese characters, showing that various pen pressure parameters are closely linked to emotional states such as enjoyment and frustration. Yu et al. [26] further demonstrated that changes in local peak pen pressure and writing speed can serve as indicators of a writer's cognitive load. Together, these findings suggest that users naturally adjust their pen pressure in response to the mental demands of a task.

Beyond serving as a passive indicator of internal states, pen pressure has also been explored as an active modality for interface control. Ramos et al. [16] introduced pressure-sensitive widgets that enable fluid, multi-parameter interactions by varying the force applied to a stylus. Sekiguchi et al. [20] proposed PP-Undo, a technique that utilizes stroke confidence determined by pen pressure to manage undo and redo operations. These interaction techniques indicate that users possess sufficient motor control to intentionally modulate pen pressure to convey information.

Taken together, prior work has treated pen pressure mainly in two ways: as a form of motor input that users intentionally modulate, and as a source of visual feedback that changes the appearance of strokes. While the former has been widely studied in the context of interaction and control, comparatively little attention has been paid to whether the visual consequences of pressure modulation function as a cognitive aid during problem-solving tasks, particularly those involving non-linear reasoning processes. Our study focuses on this latter perspective and examines whether pressure-induced visual differences in strokes support reasoning during geometry problem solving.

2.2 Research on Digital Handwriting Data in Educational Contexts

A substantial body of research has examined how digital handwriting data can support learning and instruction. Bonneton et al. [3] surveyed educators and identified strong demand for tools that assess handwriting skills to provide targeted instructional support. In response, researchers have developed systems that evaluate handwriting quality based on parameters such as stroke order, writing speed, and character shape [22, 25], demonstrating the potential of digital tablets to provide detailed, real-time analysis of handwriting traces.

Digital handwriting data has also been applied to understanding developmental and clinical aspects of writing, including changes in kinematic features across grade levels [1] and automated diagnosis of handwriting disorders [27]. In parallel, another line of research has analyzed handwriting behavior as a proxy for cognitive and attentional states. For example, Han et al. [7] identified correlations between writing behavior and overall test performance, while other studies have explored the detection of concentration lapses or task engagement through variations in pen pressure [2, 21].

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[1] Such cost and procurement driven omissions have also been informally observed in real educational deployments, where low-cost styluses without pressure sensitivity are recommended or bundled for classroom use.

These studies collectively highlight the value of digital handwriting data for skill assessment and behavioral monitoring in educational contexts.

2.3 Handwriting Features as Cognitive and Interactional Supports

Theoretical perspectives on sketching provide further insight into how such visual features might support cognition. Goel [6] characterized sketches as ambiguous and dense symbol systems, arguing that this inherent ambiguity facilitates the exploratory movement between different ideas through lateral transformations. Furthermore, Fish and Scrivener [4] observed that faint or vague marks are easily assimilated into mental images, allowing such strokes to represent a range of possibilities rather than a single, definitive answer. Similarly, Scrivener et al. [19] identified uncertainty as a primary driver of structural changes in drawing, noting that when writers are unsure, they often produce incomplete or fragmented marks.

Beyond these theoretical perspectives, educational HCI research has also shown that the design of interaction and feedback mechanisms can substantially shape learning processes and outcomes [24]. For example, immersive training systems have used interactive guidance and immediate feedback to support skill acquisition in educational settings [17]. Meta-analytic research on virtual reality-based instruction has also suggested that learning outcomes are influenced not only by the medium itself, but also by the instructional design principles embedded in interactive environments [12]. From this perspective, pen pressure in digital handwriting can be understood not merely as an input property, but as an interaction design feature whose visual feedback may influence how learners externalize, organize, and refine their reasoning.

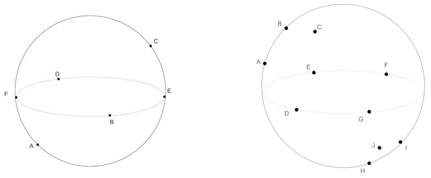
However, most existing work has focused on character formation or the inference of the writer's internal state. In contrast, limited research has examined the functional role of handwriting features as cognitive supports during problem solving. In the context of geometry learning, the theoretical functions of sketching suggest that thin, light strokes may serve as crucial visual cues that represent the tentativeness of a learner's reasoning. In particular, the impact of visually representing pen pressure through stroke darkness on learners' ability to organize information and reason through complex tasks, such as geometry problem solving, remains underexplored.

3 Experiment

3.1 Outline of the Experiment

This experiment investigates the hypothesis that problem-solving accuracy in tasks requiring trial-and-error exploration is higher in a pressure-sensitive condition than in a non-pressure-sensitive condition. To test this hypothesis, we conducted a controlled study with university students, comparing two handwriting conditions.

In the pressure-sensitive condition, the darkness of each stroke varied according to the pen pressure applied by the participant. In contrast, in the non-pressure-sensitive condition, stroke appearance remained constant regardless of applied pressure.



(a) Problem 5 **(b) Problem 6**

Figure 2: Auxiliary diagrams depicting the spheres and labeled points for the solid geometry problems.

3.2 Experimental Design

This experiment employed geometry problem-solving tasks that require iterative construction and annotation, while not demanding new conceptual learning for university-level participants. Geometry problems were selected because solving them typically involves adding auxiliary lines, marking angles, and revising diagrams, all of which are activities where variation in stroke darkness may naturally be used to represent uncertainty or intermediate steps.

The problem set consisted of six geometry tasks, as shown in Table 1. Problems 1–4 addressed plane geometry, while Problems 5 and 6 involved solid geometry. The overall difficulty was calibrated such that, provided the figures were constructed correctly, the solutions relied only on fundamental geometric knowledge commonly taught at the elementary school level in Japan, such as the angle-sum property of triangles and properties of parallel lines.

For the solid geometry problems (Problems 5 and 6), auxiliary diagrams depicting the arrangement of points on a sphere were provided in advance on the answer sheet (Figure 2). Figure 2a and Figure 2b present the supporting diagrams for Problems 5 and 6, respectively.

3.3 System

This subsection describes the handwriting system and the implementation of the pressure-sensitive and non-pressure-sensitive conditions.

The handwriting application was implemented in JavaScript and recorded all interaction logs locally. Pen pressure data were accessed through the browser-native Pointer Events API. Specifically, the application captured 'pointerdown', 'pointermove', and 'pointerup' events on the canvas and used the 'pressure' property of each 'PointerEvent' to obtain normalized pressure values in the range of 0 to 1, which were also logged locally together with stroke coordinates. In both conditions, pen pressure values were recorded identically; however, only in the pressure-sensitive condition were they used to modulate the visual darkness of strokes on the screen.

Participants performed the tasks using a Wacom MobileStudio Pro tablet with a resolution of 3840 × 2160 pixels. A Wacom Pro Pen 2 stylus, supporting 8192 levels of pressure sensitivity, was used for input.

The application interface is shown in Figure 3. The interface includes controls for selecting the problem set, starting and ending measurements, indicating the completion of diagram construction, and switching between pen and eraser modes. A 1280 × 720 pixel canvas served as the answer area.

Table 1: List of geometry tasks used in the experiment.

Problem No.	Problem Text
No.1 Plane geometry	Points A, B, C, D, E, F, and G lie on circle O. The following angles are given: "∠DAE=60°, ∠GCE=40°, ∠AFD=70°, ∠BEG=40°, ∠GCF=35°, ∠CFD=30°, ∠BGC=40°, ∠ACD=100°, ∠BEA=10°". The seven points are arranged consecutively around the circle, either in clockwise or in counterclockwise order from A to G. The interior angles of any triangle sum to 180 degrees. Determine the measure of ∠GBE.
No.2 Plane geometry	Points A, B, C, D, and E lie on circle O. The following angles are given: "∠BAC=30°, ∠CAD=40°, ∠EBD=20°, ∠ACD=40°, ∠BEC=10°, ∠CED=40°, ∠ADE=60°". The five points are arranged consecutively around the circle, either in clockwise or in counterclockwise order from A to E. The interior angles of any triangle sum to 180 degrees. Determine the measure of ∠BDE.
No.3 Plane geometry	Points A, B, C, D, and E lie on circle O. The following angles are given: "∠BAD=35°, ∠AEB=40°, ∠CDE=100°, ∠AED=80°, ∠BEC=30°". The five points are arranged consecutively around the circle, either in clockwise or in counterclockwise order from A to E. The interior angles of any triangle sum to 180 degrees. Determine the measure of ∠DCE.
No.4 Plane geometry	Points A, B, C, D, and E lie on circle O. The following angles are given: "∠CBD=20°, ∠CBE=80°, ∠BCE=60°, ∠BEC=40°, ∠BDE=60°". The five points are arranged consecutively around the circle, either in clockwise or in counterclockwise order from A to E. The interior angles of any triangle sum to 180 degrees. Determine the measure of ∠CED.
No.5 Solid geometry	Points A, B, C, D, E, and F lie on the surface of a sphere. Points A, B, C, and D are contained in one plane, while points B, E, D and F lie in another plane. The following angles are given: "∠ABC=30°, ∠BFC=30°, ∠DCF=40°, ∠ACB=60°, ∠EDB=30°, ∠BFD=60°, ∠BDF=40°, ∠BED=120°". Determine the measure of ∠EBF. (The accompanying figure shows the sphere and the arrangement of the points.)
No.6 Solid geometry	Points A, B, C, D, E, F, G, H, I, and J lie on the surface of a sphere. The points form two triangles, ABC and HIJ, and a quadrilateral DEFG. The four points A, C, H and J lie in the same plane. Triangles ABC and HIJ are parallel (their planes are parallel), and the lengths of segments HI and HJ are equal. The following angles are given: "∠BAC=30°, ∠CAE=50°, ∠DGF=120°, ∠ACH=40°, ∠HJI=60°, ∠FJI=50°". Determine the measure of ∠CHJ. (The accompanying figure shows the sphere and the arrangement of the points.)

Pen pressure values were normalized to a range of 0 to 1, with higher pressure producing darker strokes. To enhance perceptual differences in stroke darkness, a nonlinear mapping was applied to the RGB values. Previous research suggests that when changes in stroke darkness are difficult to perceive, users are less likely to intentionally modulate pen pressure. Therefore, pilot testing was conducted to determine parameters that ensured pressure-based visual feedback was clearly perceivable. The intensity factor X was computed as follows:

$$\begin{cases} X = 8\,(pressure)^4 & (pressure \leq 0.5)\ \cdots ① \\ X = 1 - \dfrac{(-2\,pressure + 2)^4}{2} & (pressure > 0.5)\ \cdots ② \end{cases}$$

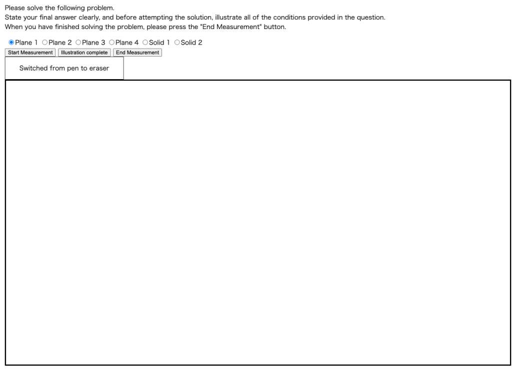
The final RGB values were calculated as:

$$RGB = (1 - X) \times 255$$

In the non-pressure-sensitive condition, stroke appearance was fixed to simulate styluses commonly used in educational settings where pen pressure detection is omitted due to budget constraints. This design allowed us to evaluate the impact of cost-driven design decisions on learning behavior.

3.4 Experimental Procedure

All participants followed the same experimental procedure, which began with a pen-pressure calibration phase during which they drew strokes using both light and heavy pressure to establish their individual dynamic ranges. After calibration, participants clicked the “Start Measurement” button and constructed the geometric diagram within the answer area.



Please solve the following problem.
State your final answer clearly, and before attempting the solution, illustrate all of the conditions provided in the question.
When you have finished solving the problem, please press the "End Measurement" button.

Figure 3: Interface of the handwriting application used in the experiment.

Once the diagram was completed, participants pressed the “Illustration Complete” button, which triggered the display of the specific geometry problem to be solved. After reaching a solution, participants clicked the “End Measurement” button to conclude the task and proceed to the next problem. This sequence was repeated for Problems 1 through 6 in a fixed order for all participants.

A total of 40 undergraduate and graduate students (33 men, 7 women) participated in the study. Participants were evenly assigned to the pressure-sensitive and non-pressure-sensitive conditions. Due to missing data from one participant in each condition, the final analysis was conducted using data from 19 participants per condition.

4 Results

4.1 Overall Accuracy

Figure 4 shows the distribution of the total number of correct answers across all six problems for the two conditions.

In the pressure-sensitive condition, the first quartile was 4 and the median was 4.58. In the non-pressure-sensitive condition, the first quartile was 3 and the median was 4.42. The mean accuracy rate across all problems was 76.3% in the pressure-sensitive condition and 73.7% in the non-pressure-sensitive condition.

4.2 Accuracy by Problem

Figure 5 and Table 2 present the accuracy rates for each individual problem under the pressure-sensitive and non-pressure-sensitive conditions. To examine whether accuracy differed between conditions for each problem, we compared the numbers of correct and incorrect responses using Fisher's exact test. Because six problem-wise comparisons were conducted, Holm's correction was applied to the resulting p values. As shown in Table 2, Problems 1 and 5 showed higher accuracy in the pressure-sensitive condition than in the non-pressure-sensitive condition, whereas Problems 2, 3, and 4 showed higher accuracy in the non-pressure-sensitive condition, and Problem 6 showed the same accuracy in both conditions. However, no individual problem remained significant after Holm correction.

We further conducted a grouped analysis by dividing the problems into the first-encountered problems (Problems 1 and 5) and the later problems (Problems 2, 3, 4, and 6). For each participant, we calculated the number of correct answers for each group and compared the two conditions using Mann–Whitney U tests, with rank-biserial correlation as the effect size. For the first-encountered problems, the pressure-sensitive condition showed significantly higher scores than the non-pressure-sensitive condition ($U = 257.0$, $p = .013$, $r_{rb} = .424$). For the later problems, no significant difference was found between conditions ($U = 138.0$, $p = .191$, $r_{rb} = -.235$).

4.3 Completion Time

Figure 6 presents the average completion time for each problem under the pressure-sensitive and non-pressure-sensitive conditions, with numerical values shown above the bars.

For Problems 1, 2, and 3, the average completion time tended to be higher in the pressure-sensitive condition than in the non-pressure-sensitive condition. In contrast, for Problems 4, 5, and 6, the average completion time tended to be higher in the non-pressure-sensitive condition.

4.4 Distribution of Pen Pressure

Figure 7 summarizes the distribution of pen pressure values across all participants.

The horizontal axis represents normalized pen pressure values ranging from 0 to 1, and the vertical axis indicates frequency. Compared to the non-pressure-sensitive condition, participants in the pressure-sensitive condition more frequently used higher pressure values near 1.0 and less frequently used lower pressure values.

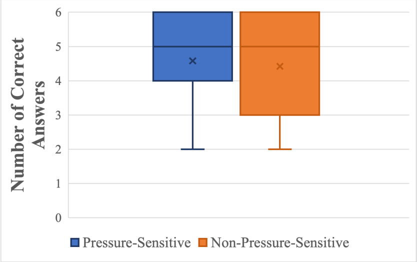


Figure 4: Comparison of the number of correct answers between the pressure-sensitive and non-pressure-sensitive conditions.

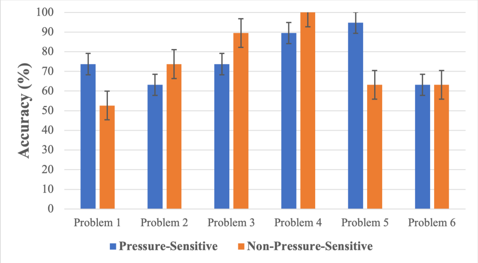


Figure 5: Comparison of accuracy rates by problem for the pressure-sensitive and non-pressure-sensitive conditions.

Table 2: Accuracy by condition and statistical comparisons for each problem.

Problem	Pressure-Sensitive (%)	Non-Pressure-Sensitive (%)	Raw p	Holm-adjusted p
Problem 1	73.68	52.63	.313	1.000
Problem 2	63.16	73.68	.728	1.000
Problem 3	73.68	89.47	.405	1.000
Problem 4	89.47	100.00	.486	1.000
Problem 5	94.74	63.16	.042	.253
Problem 6	63.16	63.16	1.000	1.000

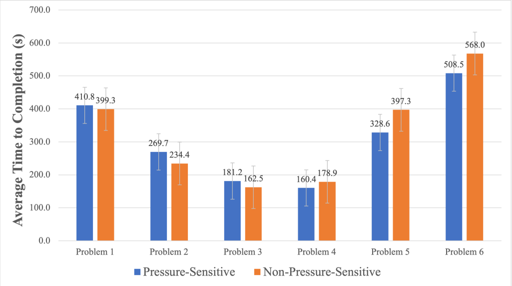


Figure 6: Average completion time for each problem in the pressure-sensitive and non-pressure-sensitive conditions. Numerical values are shown above the bars.

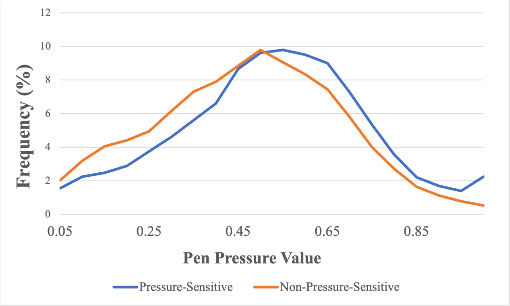


Figure 7: Distribution of pen pressure values for the pressure-sensitive and non-pressure-sensitive conditions.

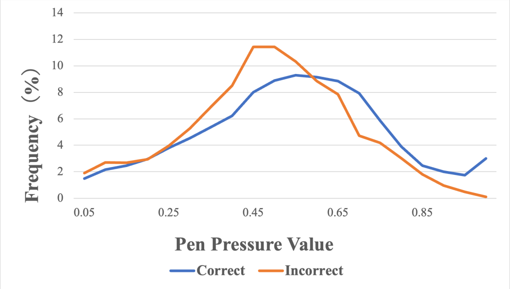


Figure 8: Comparison of pen pressure distributions between correct and incorrect responses in the pressure-sensitive condition.

5 Discussion

5.1 Effect of Pen Pressure Representation on Accuracy in Geometry Problems

Although the mean and median numbers of correct answers were comparable between the pressure-sensitive and non-pressure-sensitive conditions, the distributional analysis revealed a meaningful asymmetry. As shown in Figure 4, the lower tail of the distribution differed clearly between conditions: the first quartile was lower in the non-pressure-sensitive condition, and a larger number of participants fell into the low-performance range.

This pattern suggests that the absence of pen-pressure-based stroke modulation does not uniformly degrade performance, but rather disproportionately affects a subset of learners. Education is increasingly expected to be designed with an inclusive approach that accounts for learner diversity and is grounded in principles of equity [8, 15]. From an educational perspective, pen pressure may function as a form of cognitive scaffolding that supports learners who otherwise struggle to maintain visual organization during problem solving. Omitting pressure sensitivity for reasons such as cost reduction may therefore increase the risk of widening performance disparities in digital learning environments.

A problem-wise examination further clarified this tendency. As illustrated in Figure 5, lower accuracy in the non-pressure-sensitive condition was particularly evident in Problem 1 and Problem 5, which were the first-encountered tasks in the plane and solid geometry sets, respectively. In these first-encountered problems, participants were required to actively explore solution strategies before adapting to the task structure. This tendency was also supported by the grouped analysis.

This interpretation is reinforced by the relationship between response time and accuracy shown in Figure 6. In the non-pressure-sensitive condition, longer completion times were often associated with lower accuracy, suggesting that increased effort did not necessarily translate into successful problem solving. Taken together, these findings suggest that pen-pressure-based stroke modulation may be especially beneficial in unfamiliar or cognitively demanding situations that require iterative diagram construction and revision.

Overall, while pen pressure did not universally improve accuracy across all tasks, its benefits emerged selectively—particularly in contexts where exploratory reasoning and visual organization play a central role.

5.2 Relationship Between Pen Pressure Usage and Problem-Solving Outcomes

The analysis of pen pressure usage provides further insight into this selective benefit. As shown in Figure 8, correctly solved problems in the pressure-sensitive condition were characterized by a broad distribution of pressure values spanning the full range. This pattern indicates that participants actively exploited stroke darkness variation when problem solving was successful.

In contrast, incorrect responses in the pressure-sensitive condition exhibited a more concentrated pressure distribution, closely resembling the pattern observed in the non-pressure-sensitive condition (Figure 7). High-pressure strokes were rarely used in these cases, suggesting limited engagement with pressure-based visual differentiation.

These observations point to a bidirectional relationship between pen pressure usage and cognition. On the one hand, pressure modulation may support problem solving by enabling effective visual hierarchy and information organization. On the other hand, reduced variation in pressure may reflect uncertainty or the absence of a clear solution strategy. This dual role implies that pen pressure dynamics may function not only as a cognitive aid but also as an implicit indicator of learners' problem-solving states.

5.3 Qualitative Analysis of Problem-Solving Errors

- *Calculation Error*: Numerical mistakes during arithmetic operations, independent of geometric reasoning.
- *Drawing Error*: Errors in constructing the geometric diagram itself.
- *Answering Error*: Calculating an angle or value other than the one explicitly requested.
- *Misreading*: Correct construction followed by the use of incorrect values extracted from the diagram.
- *Other*: Cases where participants failed to reach a solution or reported being unable to solve the problem.

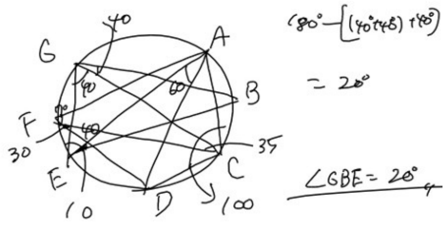


Figure 9: An example of a calculation error in the non-pressure-sensitive condition (Problem 1), where the participant failed to correctly subtract multiple angles.

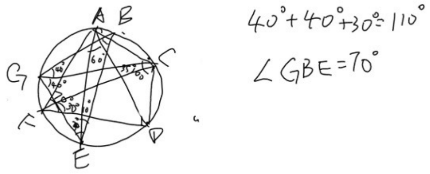


Figure 10: An example of a drawing error in the non-pressure-sensitive condition (Problem 1), where the participant misinterpreted ∠BEG as 30° because the stroke for ∠AEG extended beyond its intended area.

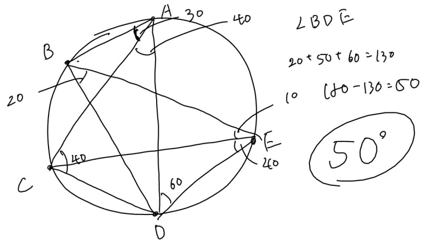


Figure 11: An example of an answering error in the non-pressure-sensitive condition (Problem 2), where the participant calculated an irrelevant angle (∠ADE) instead of the target angle (∠BDE).

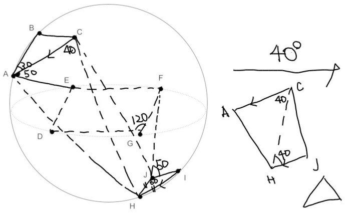


Figure 12: An example of a response to the solid geometry task in the non-pressure-sensitive condition. Uniform stroke darkness makes it difficult to distinguish auxiliary elements from the edges of the solid and to perceive depth.

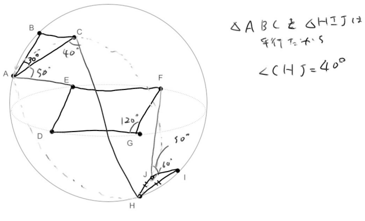


Figure 13: An example of a response to the solid geometry task in the pressure-sensitive condition. Varying levels of stroke darkness provide clear depth cues and differentiate annotations from the primary geometric shape.

Importantly, this categorization was not intended as a formal outcome measure, but as an interpretive lens to explain how the absence of pen-pressure-based visual differentiation affected problem-solving processes.

Representative examples illustrate how the absence of pen-pressure-based modulation can exacerbate specific error types. Figure 9 shows a calculation error in which uniform stroke darkness made it difficult to visually prioritize components of a lengthy expression, potentially increasing cognitive load. Figure 10 demonstrates a drawing error caused by stroke overextension, where the inability to gradually fade strokes introduced visual ambiguity and led to misinterpretation of angle information.

By contrast, answering errors, such as selecting an incorrect target angle (Figure 11), occurred with similar frequency in both conditions. This suggests that pen pressure primarily affects errors related to visual organization and diagram interpretation rather than misunderstandings of task instructions.

The effect of stroke modulation was particularly evident in solid geometry tasks. In the non-pressure-sensitive condition (Figure 12), auxiliary elements and structural edges were rendered with identical stroke darkness, obscuring depth cues and relationships. In contrast, pressure-sensitive diagrams (Figure 13) leveraged variations in stroke darkness to distinguish annotations from primary structures and convey spatial depth more effectively.

5.4 Compensatory Diagramming Strategies

Finally, qualitative inspection revealed that participants adopted compensatory strategies when pressure-based modulation was unavailable. In the pressure-sensitive condition, some participants strategically emphasized critical information, such as angle-related annotations, using darker strokes, even when this deviated from conventional drawing practices (Figure 14). This behavior illustrates flexible and intentional use of pen pressure as a representational resource.

Conversely, in the non-pressure-sensitive condition, some participants relocated annotations outside the main figure in order to reduce visual clutter (Figure 15). While this spatial separation partially compensated for the lack of stroke differentiation, it also increased diagram complexity and may have imposed additional cognitive demands.

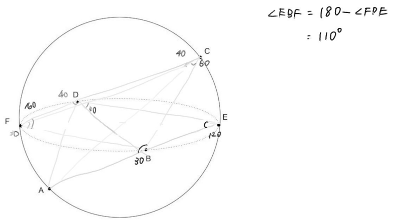


Figure 14: Strategic use of pen pressure in the pressure-sensitive condition: emphasizing angle-related information with darker strokes to enhance task-specific clarity.

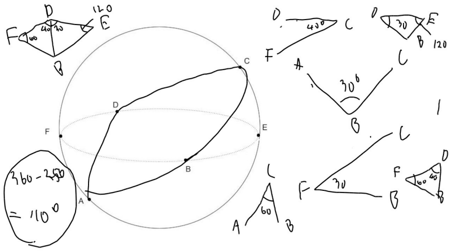


Figure 15: Spatial strategy in the non-pressure-sensitive condition: placing annotations outside the figure to compensate for the absence of stroke darkness modulation.

These adaptive behaviors reinforce the interpretation that pen pressure functions not merely as an expressive feature but as a cognitive resource that supports visual reasoning. When such pressure-based modulation is unavailable, learners restructure their diagramming strategies to compensate, highlighting the educational significance of pressure sensitivity as a design decision in digital handwriting environments.

5.5 Limitations

The findings of this study should be interpreted in light of several limitations.

First, the experimental tasks were limited to plane and solid geometry problems that strongly relied on diagram construction and visual annotation. While this focus allowed us to closely examine the role of stroke darkness in visual reasoning, the observed effects may not generalize to learning activities that involve less diagrammatic thinking, such as purely symbolic or text-based tasks.

Second, although the geometric knowledge required to solve the problems corresponded to an elementary school level, all participants were university students. This design choice helped control for prior knowledge but does not fully capture the cognitive and motor characteristics of younger learners in real classroom settings.

Third, the relationship between pen pressure usage and problem-solving performance cannot be interpreted as strictly causal. As discussed earlier, pressure modulation may both support visual organization and reflect learners' confidence or understanding. Future studies that manipulate pressure feedback independently or adopt longitudinal designs will be necessary to disentangle these factors.

Finally, the categorization of problem-solving errors was used as an interpretive lens rather than as a formal quantitative outcome. While this qualitative analysis provided insight into how the absence of pressure modulation affected diagramming behavior, future work should incorporate systematic coding procedures and inter-rater reliability measures.

6 Conclusion

This study examined the role of pen pressure sensitivity in educational digital handwriting, focusing on whether pressure-based variation in stroke darkness supports problem solving in geometry tasks. While no statistically significant difference was found in overall average accuracy between conditions, participants in the non-pressure-sensitive condition showed noticeably lower performance when solving unfamiliar or cognitively demanding problems. In addition, solution times were significantly longer for solid geometry tasks when pen pressure was unavailable. These results suggest that uniform stroke appearance may increase visual and cognitive load, particularly when learners must reason about complex spatial relationships.

Qualitative analyses further contextualized these findings. Participants in the pressure-sensitive condition actively used variations in stroke darkness to organize visual hierarchy and convey depth, supporting iterative trial-and-error reasoning. In contrast, participants without pressure sensitivity adopted compensatory strategies, such as relocating annotations outside the main figure, to manage visual ambiguity. While partially effective, these strategies often increased diagram complexity and cognitive effort.

Taken together, our findings suggest that omitting pen pressure for cost or procurement reasons is not a cognitively neutral design choice. Doing so can undermine the effectiveness of digital handwriting as a tool for mathematical reasoning and spatial problem solving, particularly for learners who rely on visual organization during exploration. These results highlight the educational importance of pen pressure as a representational resource and suggest that designers of digital handwriting environments should prioritize pressure sensitivity in tasks that involve exploratory diagram construction. Although this study did not directly examine younger learners, the findings suggest that pressure-based stroke differentiation may be particularly valuable in classroom activities that require drawing, annotation, and visual organization, because it may allow learners to externalize and manipulate their thinking more intuitively.

Future work will investigate tasks with even higher cognitive demands to further isolate the effects of pressure-based modulation. We also plan to conduct longitudinal studies to examine whether pen pressure supports deeper conceptual understanding over extended learning periods.

References

[1] Agostino P Accardo, Mariangela Genna, and Michela Borean. 2013. Reprint of 'Development, maturation and learning influence on handwriting kinematics'. *Human movement science* 32, 5 (2013), 999–1009.

[2] Gaddi Blumrosen, Katsuyuki Sakuma, John Jeremy Rice, and John Knickerbocker. 2020. Back to finger-writing: Fingertip writing technology based on pressure sensing. *Ieee Access* 8 (2020), 35455–35468.

[3] Nathalie Bonneton-Botte, Claude Beucher-Marsal, Florence Bara, Julie Muller, Laurence Le Corf, Marielle Quéméneur, and Maud Dare. 2021. Teaching cursive handwriting: A contribution to the acceptability study of using digital tablets in French classrooms. *Journal of Early Childhood Literacy* 21, 2 (2021), 259–282.

[4] Jonathan Fish and Stephen Scrivener. 1990. Amplifying the mind's eye: sketching and visual cognition. *Leonardo* 23, 1 (1990), 117–126.

[5] Abraham E Flanigan, Jordan Wheeler, Tiphaine Colliot, Junrong Lu, and Kenneth A Kiewra. 2024. Typed versus handwritten lecture notes and college student achievement: A meta-analysis. *Educational Psychology Review* 36, 3 (2024), 78.

[6] Vinod Goel. 1995. *Sketches of thought.* MIT press.

[7] Laiquan Han, Bo Pan, Ying Chen, and Jianhua Tang. 2024. A digital pen-based writing state recognition algorithm for student performance assessment. *Neural Computing and Applications* (2024), 1–11.

[8] Mike Kent. 2015. Disability and eLearning: Opportunities and barriers. *Disability Studies Quarterly* 35, 1 (2015).

[9] Markus Kiefer, Stefanie Schuler, Carmen Mayer, Natalie M Trumpp, Katrin Hille, and Steffi Sachse. 2015. Handwriting or typewriting? The influence of pen-or keyboard-based writing training on reading and writing performance in preschool children. *Advances in cognitive psychology* 11, 4 (2015), 136.

[10] Sari Kobayashi, Yuto Sekiguchi, Riho Ueki, Satoshi Nakamura, and Akiyuki Kake. 2025. Does Representing Pen Pressure Improve Handwritten Calculation Accuracy? *Procedia Computer Science* 270 (2025), 2808–2817.

[11] Birgy Lorenz, Kaido Kikkas, and Mart Laanpere. 2016. Digital Turn in the schools of Estonia: Obstacles and Solutions. In *International Conference on Learning and Collaboration Technologies*. Springer, 722–731.

[12] Zahira Merchant, Ernest T Goetz, Lauren Cifuentes, Wendy Keeney-Kennicutt, and Trina J Davis. 2014. Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & education* 70 (2014), 29–40.

[13] Ministry of Education, Culture, Sports, Science and Technology (MEXT). 2023. Status of One Device per Student in Compulsory Education: As of the End of FY2022. https://www.mext.go.jp/a_menu/other/mext_00921.html. in Japanese. Last accessed: April 10, 2026.

[14] Pam A Mueller and Daniel M Oppenheimer. 2014. The pen is mightier than the keyboard: Advantages of longhand over laptop note taking. *Psychological science* 25, 6 (2014), 1159–1168.

[15] Carmen del Rosario Navas-Bonilla, Julio Andrés Guerra-Arango, Daniel Alejandro Oviedo-Guado, and Daniel Eduardo Murillo-Noriega. 2025. Inclusive education through technology: a systematic review of types, tools and characteristics. In *Frontiers in Education*, Vol. 10. Frontiers Media SA, 1527851.

[16] Gonzalo Ramos, Matthew Boulos, and Ravin Balakrishnan. 2004. Pressure widgets. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 487–494.

[17] Luigia Rizzo, Domenico Rossi, Marco Giammetti, and Paola Barra. 2025. Simulation system for dental bracket positioning. In *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 604–610.

[18] Claudia Schrader and Slava Kalyuga. 2020. Linking students' emotions to engagement and writing performance when learning Japanese letters with a pen-based tablet: An investigation based on individual pen pressure parameters. *International Journal of Human-Computer Studies* 135 (2020), 102374.

[19] Stephen AR Scrivener, Linden J Ball, and Winger Tseng. 2000. Uncertainty and sketching behaviour. *Design Studies* 21, 5 (2000), 465–481.

[20] Yuto Sekiguchi, Riho Ueki, and Satoshi Nakamura. 2023. PP-Undo: An Undo/Redo Technique Based on Stroke Confidence Derived from Pen Pressure Control. In *Proceedings of the Human-Computer Interaction Research Group, Information Processing Society of Japan (IPSJ SIG Technical Report, Vol. 2023-HCI-201)*. 1–8. In Japanese.

[21] A Sheerin, N Palanivel, J Sheerin Farhana, P Vishnupriya, R Abishaa, and E Janani. 2024. Smart Pen Utilizing IoT for Detection of Concentration Lapses During Writing. In *2024 International Conference on System, Computation, Automation and Networking (ICSCAN)*. IEEE, 1–7.

[22] Damien Simonnet, Eric Anquetil, and Manuel Bouillon. 2017. Multi-criteria handwriting quality analysis with online fuzzy models. *Pattern Recognition* 69 (2017), 310–324.

[23] Elisha Tushara. 2023. MOE, schools looking to improve primary pupils' digital literacy skills. https://www.straitstimes.com/singapore/moe-schools-looking-to-improve-primary-school-pupils-digital-literacy.

[24] Jennifer J Vogel, David S Vogel, Jan Cannon-Bowers, Clint A Bowers, Kathryn Muse, and Michelle Wright. 2006. Computer gaming and interactive simulations for learning: A meta-analysis. *Journal of educational computing research* 34, 3 (2006), 229–243.

[25] Toshinori Yamasaki, Tetsuo Hattori, and Seiji Inokuchi. 1990. An adaptive real time training system for beautiful handwriting of japanese letters. In *1990 IEEE International Conference on Systems, Man, and Cybernetics Conference Proceedings*. IEEE, 88–93.

[26] Kun Yu, Julien Epps, and Fang Chen. 2011. Cognitive load evaluation of handwriting using stroke-level features. In *Proceedings of the 16th international conference on Intelligent user interfaces*. 423–426.

[27] Konrad Zolna, Thibault Asselborn, Caroline Jolly, Laurence Casteran, Wafa Johal, Pierre Dillenbourg, et al. 2019. The dynamics of handwriting improves the automated diagnosis of dysgraphia. *arXiv preprint arXiv:1906.07576* (2019).