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Does Representing Pen Pressure Improve Handwritten Calculation Accuracy?

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Abstract

With the digitization of education, opportunities for handwritten input using tablets and other digital devices have increased. However, the impact of digital handwriting on problem-solving performance and its contributing factors remains unclear. This study focuses on pen pressure, a fundamental element of handwriting, and investigates how pressure sensitivity affects arithmetic problem-solving. We hypothesized that allowing users to vary stroke darkness through pen pressure would enhance accuracy. To test this, we conducted an experiment comparing a pressure-sensitive condition, where pen pressure affected stroke darkness, and a non-pressure-sensitive condition, where stroke darkness was uniform. University students solved arithmetic problems involving addition, subtraction, multiplication, and division. The results showed no significant difference in accuracy for addition, subtraction, or multiplication, but significantly higher accuracy in division problems under the pressure-sensitive condition. Pen pressure analysis also revealed differences in value distribution between conditions. Furthermore, error analysis suggested that the inability to modulate stroke darkness might lead to misinterpretation of auxiliary digits or other handwritten calculation marks during complex tasks. These findings indicate that pen pressure sensitivity may support more effective problem-solving in arithmetic tasks that involve complex, multi-step reasoning, by improving the visual clarity of handwritten information.

Keywords: pen pressure; calculation accuracy; handwritten calculation; digital tablet;digital education; digital handwriting

1. Introduction

Devices that support handwriting input, such as smartphones and tablets, have become widely used. These digital handwriting-enabled devices are increasingly being introduced into educational settings, providing students with more

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opportunities to engage in digital handwriting. According to a 2023 survey by the Japanese Ministry of Education, Culture, Sports, Science and Technology, 99.9% of local governments across Japan have supplied learning devices to all elementary and junior high school students, ensuring universal access to digital learning environments [1]. In the United States, Lewis Elementary School reported increased student enrollment and attendance rates following the integration of iPads into the curriculum. These devices are used for activities such as transcribing notes from the board and solving problems using educational applications [2].

Prior research suggests that handwritten notes are more effective for learning than typing on a laptop [3][4], and the number of digital device users in educational settings is expected to continue increasing. However, the impact of replacing paper and pencil with digital devices remains insufficiently understood, particularly with regard to the factors that should be considered in this transition.

One important characteristic of handwriting with paper and pencil is that the pressure applied can naturally adjust the darkness of lines. This characteristic enables faster and more intuitive adjustments to the visibility of handwritten content compared to manual modifications of pen color or stroke thickness. Consequently, pressure-sensitive pens and software have been developed to enable similar functionality in digital handwriting. In the GIGA School Initiative [5], which is a Japanese government program aimed at providing each student with a personal digital device, touch pens are essential tools for annotating digital teaching materials and writing mathematical expressions. Therefore, it is necessary to select their specifications based on specific usage scenarios in schools. However, due to budget constraints, the touch pens that come with tablets may not support pen pressure detection.

In educational contexts, the inability to express pen pressure may make effective handwriting more difficult when doing mathematics. In arithmetic calculations, students often write carried or borrowed numbers lightly. In geometry problems, they may darken lines and angles they are confident in while keeping uncertain elements faint. If students cannot easily control the darkness of their handwriting, it may lead to readability issues, frustration, and ultimately a negative impact on problem-solving efficiency.

This study investigates the effect of pen pressure in digital handwriting on arithmetic calculations. We hypothesize that allowing pen pressure to influence stroke darkness will improve problem-solving accuracy compared to fixed-darkness conditions. By exploring the role of pen pressure in handwritten calculations, we aim to assess its educational significance and provide insights for the design of pressure-sensitive styluses and adaptive digital handwriting environments.

The contributions of this study are summarized as follows:

- We demonstrate that representing pen pressure leads to higher accuracy in long division tasks, which typically require auxiliary digits such as carried or borrowed numbers, compared to when such representation is absent. This highlights the potential benefit of pressure sensitivity in digital handwriting environments.
- We reveal that the distribution of pen pressure values differs significantly between pressure-sensitive and non-pressure-sensitive conditions, indicating measurable behavioral differences.
- We show through error analysis that the inability to adjust stroke darkness via pen pressure may lead to misinterpretation of auxiliary digits or other handwritten calculation marks during arithmetic operations.

2. Related Work

2.1. Research on Pen Pressure

Many studies have investigated the relationship between learning and pen pressure. Schrader et al.[6] conducted an experiment using a pen type tablet to investigate the relationship between learners' emotions, motivation, and handwriting skills in learning Japanese characters. Their results showed that all of the pen pressure values were related to emotions such as enjoyment and frustration. Yu et al.[7] found that the writers' cognitive load was associated with changes in local peak pen pressure and writing speed. These observations suggest that users may have been actively adjusting pen pressure. In addition, some studies have focused on the fact that pen pressure data remains largely underutilized, and have proposed methods that allow users to control and operate interfaces through pen pressure on tablets, thereby demonstrating the potential of pressure sensitive input[8] [9].

This study investigates the relationship between the presence or absence of pen pressure induced variation in stroke darkness and calculation accuracy.

2.2. Research on Digital Handwriting in Educational Settings

Many studies have been conducted with the aim of utilizing digital handwriting. A clear need has been identified for tools that support handwriting instruction through the assessment of writing skills [10], and systems have been proposed to evaluate handwriting skills based on stroke order, character shape, writing speed, and spatial arrangement, as well as methods to assess handwriting quality based on stroke order, character shape, and writing direction [11][12]. The approach by Simonnet et al. [12] received positive feedback from both students and teachers, demonstrating the potential of stylus-equipped tablets to analyze handwriting traces and provide real-time feedback to students. Neumann et al. [13] showed that a handwriting training app providing feedback based on character shapes was effective for kindergarten students who had shown moderate performance in pre-tests. In addition, Zolna et al. [14] demonstrated that more than 90% of children diagnosed with handwriting disorders could be accurately identified.

On the other hand, some approaches focus on evaluating handwriting behavior itself. It has been shown that writing speed in horizontal and curved movements increases with grade level, that fingertip pressure variations during handwriting can be converted into signals for character recognition, and that abrupt changes in pen pressure can be used to identify inattentive states during handwriting [15][16][17]. These results indicate that handwriting data obtained from tablets can be highly useful for supporting education.

This study aims to explore how pen pressure data can be utilized to support education by experimentally examining the effects of pressure-induced variation in stroke darkness.

3. Experiment

3.1. Outline of the Experiment

This experiment aims to test the hypothesis that "when stroke darkness varies with pen pressure, problem-solving accuracy will be higher compared to when darkness remains constant." Ideally, the target participants for this experiment would be elementary and middle school students; however, as an initial study, we first conducted the experiment with university students.

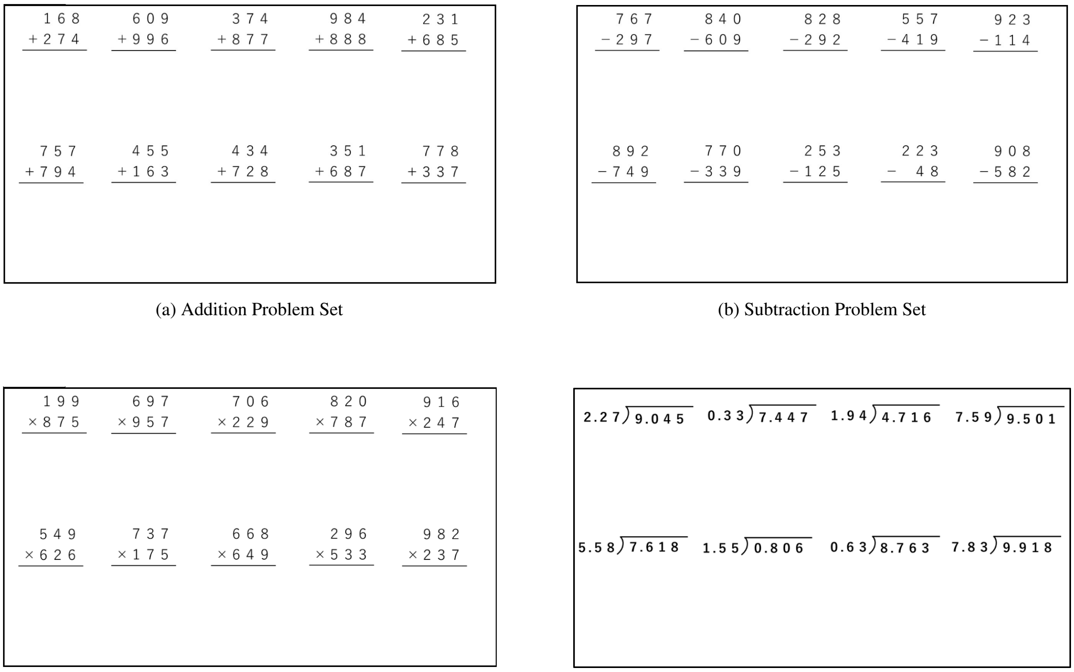
We compared two conditions: one in which the darkness of the strokes drawn by the user varies with pen pressure (the pressure-sensitive condition) and one in which the darkness remains constant regardless of pen pressure (the non-pressure-sensitive condition).

3.2. Experimental Design

In this experiment, we selected arithmetic problems (addition, subtraction, multiplication, and division) because they often involve writing small auxiliary numbers (e.g., carried or borrowed digits), which may naturally lead to adjustments in stroke darkness. We considered that the frequent use of such auxiliary markings would provide a suitable context for examining the importance of pen pressure in digital handwriting. Such behavior is particularly relevant for evaluating the effect of pen pressure sensitivity. It should be noted that, since the experiment was conducted with Japanese university students, all written calculations followed the Japanese style.

The set of arithmetic problems used in the experiment is shown in Figures 1 (a) to 1 (d). Each problem set contains 10 addition problems, 10 subtraction problems, 10 multiplication problems, and 8 division problems. The addition, subtraction, and multiplication problems involved three-digit calculations, while the division problems involved four-digit calculations. In the division problems, shifting the decimal point was required, which was intended to induce more complex and varied auxiliary markings.

The problems were arranged with minimal margins around the workspace, similar to academic tests or mock examinations, where students are required to perform calculations within a limited area. In such constrained spaces, it is assumed that students may adjust stroke darkness through pen pressure to improve the visibility of their handwritten notes.



(a) Addition Problem Set

(b) Subtraction Problem Set

(c) Multiplication Problem Set

(d) Division Problem Set

Fig. 1: Comparison of four types of problem sets. For division problems, if the numbers cannot be evenly divided, participants are asked to provide the first three digits of the quotient and the remainder.

3.3. System

The handwriting application used in the experiment was implemented using JavaScript, PHP, and MySQL. For the handwriting input tablet, we used the Wacom MobileStudio Pro, a mobile device from Wacom that features a 3840×2160 pixel display. The stylus pen was Wacom Pro Pen 2 (8192 pressure points).

The interface of the application used in the experiment is shown in Figure 2. The screen displays radio buttons for selecting the problem set, a button to start measurement, a button to end measurement, buttons to switch between pen and eraser modes, and an area displaying arithmetic problems (1280×720 pixels) along with answer fields. Pen pressure takes values from 0 to 1, with higher pressure resulting in darker stroke colors. Each RGB channel is calculated using the formula: $(1 - pressure) \times 255$. This results in grayscale strokes that become darker with increased pressure.

When the "Start Measurement" button is pressed, a countdown of 600 seconds begins, and the user can start writing. Participants write on an image of the problem using a pen, while the system records pen pressure and response time for each stroke. Users can switch between writing and erasing modes at any time using the mode change button. After completing the calculations, pressing the "End Measurement" button stops the countdown, disables input, and saves all stroke data including pen pressure. The system also automatically captures a screenshot of the answer field at this point.

3.4. Experimental Procedure

In the experiment, each problem set had a time limit of 600 seconds. Participants were instructed to press the start button when they began solving the problems and to write their answers in the designated answer fields. The answering process was considered complete when the participant pressed the stop button after finishing the problems or when the 600 seconds time limit was reached.

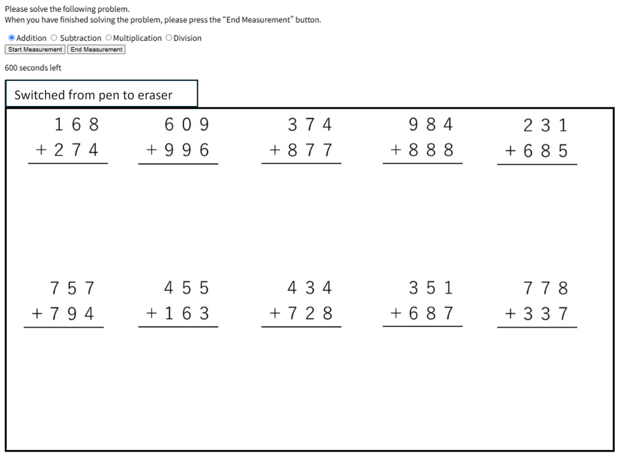


Fig. 2: Calculation System Interface.

To ensure consistency in the problem order, the sequence of operations(addition, subtraction, multiplication, and division) was fixed for all participants. The university and graduate students were divided into two groups: 10 participants in the pressure-sensitive condition and 10 in the non-pressure-sensitive condition ($n = 20$).

4. Results

To calculate the accuracy rate, we excluded unanswered questions from the analysis, as some participants ran out of time before completing all problems. This exclusion was made because the primary goal of the task was to evaluate calculation accuracy, and including unanswered items could have introduced bias due to individual differences in problem-solving speed.

We also excluded one response to a division problem in which the participant misunderstood the rules of long division. In addition, we removed data from two participants whose answers deviated substantially from the expected values, indicating a misunderstanding of how to express non-integer quotients. In this study, we used accuracy and response time as evaluation metrics. We hypothesized that differences in stroke visibility and ease of organizing written information, depending on the presence or absence of pen pressure representation, would directly impact problem-solving performance. Specifically, clearer and more informative strokes were expected to reduce errors and cognitive load during calculations, resulting in higher accuracy and faster responses.

4.1. The Average Accuracy Rate

The overall average accuracy rate was 92.2% in the pressure-sensitive condition and 87.9% in the non-pressure-sensitive condition, indicating that accuracy was higher when pen pressure sensitivity was available.

To compare the average accuracy rates for each type of calculation under the conditions, we first examined addition and subtraction, and found that the accuracy rate was 99.0% for both conditions. This suggests that these problems may have been too easy.

Figure 3 presents the accuracy rates for multiplication and division under both conditions. For multiplication, the accuracy rate was 85.0% in the pressure-sensitive condition and 86.4% in the non-pressure-sensitive condition. A t-test showed no significant difference in multiplication accuracy between the two conditions ($p > 0.05$).

In contrast, for division, the accuracy rate was 86.0% in the pressure-sensitive condition and 67.2% in the non-pressure-sensitive condition, indicating a higher accuracy rate with pressure sensitivity. An independent t-test confirmed a statistically significant difference between the two conditions at the 5% significance level ($p < 0.05$), suggesting that pressure sensitivity had a meaningful impact on division accuracy.

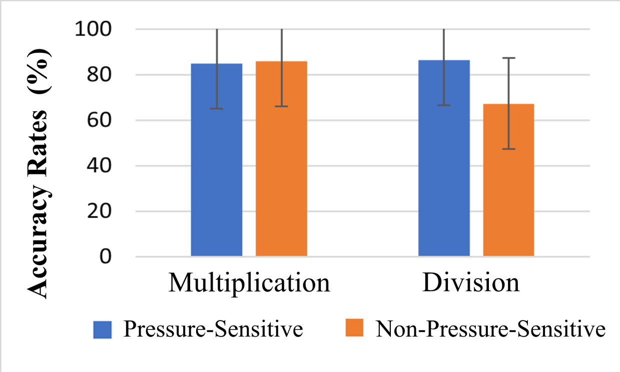


Fig. 3: Accuracy rates for multiplication and division problems under the pressure-sensitive and non-pressure-sensitive conditions.

4.2. Calculation Time

Figure 4 presents the average response time per question under the pressure-sensitive and non-pressure-sensitive conditions. For multiplication, the average response time was 42.4 seconds in the pressure-sensitive condition and 44.1 seconds in the non-pressure-sensitive condition. For division, the average response time was 74.5 seconds in the pressure-sensitive condition and 85.7 seconds in the non-pressure-sensitive condition. Although the response time for division tended to be longer in the non-pressure-sensitive condition, this difference was not statistically significant ($p > 0.05$).

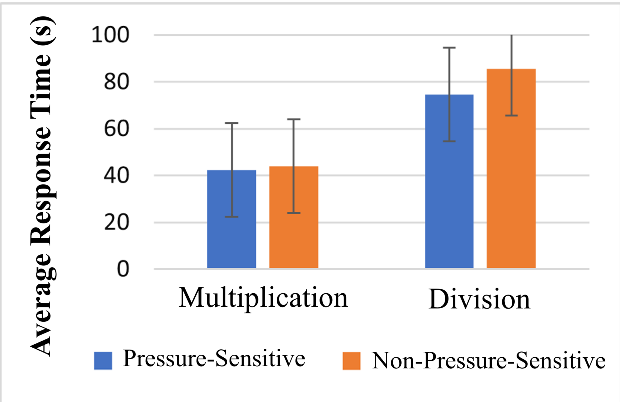
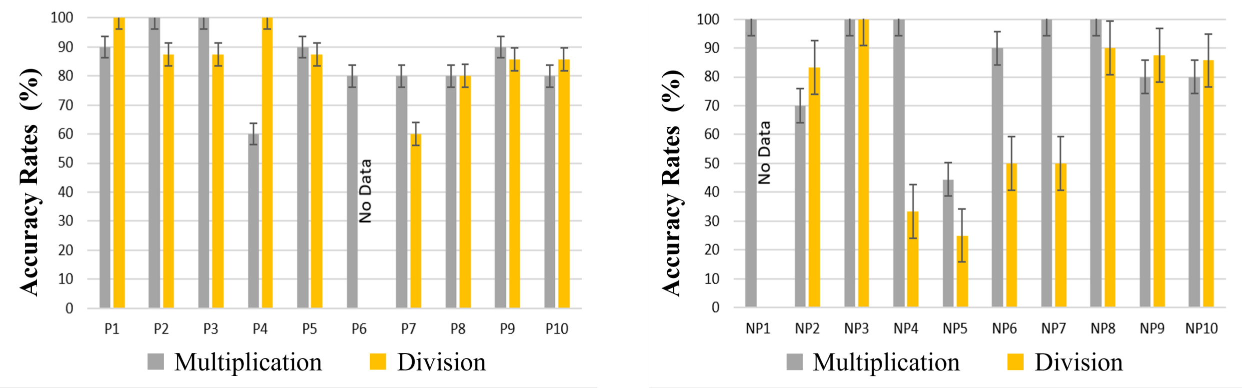


Fig. 4: Calculation time for multiplication and division problems under the pressure-sensitive and non-pressure-sensitive conditions.

4.3. Average Accuracy Rate Per Participant

Figures 5a and 5b present the accuracy rates for each participant under the pressure-sensitive and non-pressure-sensitive conditions, respectively. Participants in the pressure-sensitive condition are labeled as P1, P2, ..., P10, while those in the non-pressure-sensitive condition are labeled as NP1, NP2, ..., NP10.

The results indicate that in the pressure-sensitive condition, the accuracy rate for division did not differ significantly from that for multiplication. In contrast, in the non-pressure-sensitive condition, the accuracy rate for division was 17.7% lower than that for multiplication. These findings suggest that under the non-pressure-sensitive condition, participants generally exhibited lower accuracy in division compared to multiplication, regardless of their performance on multiplication tasks.



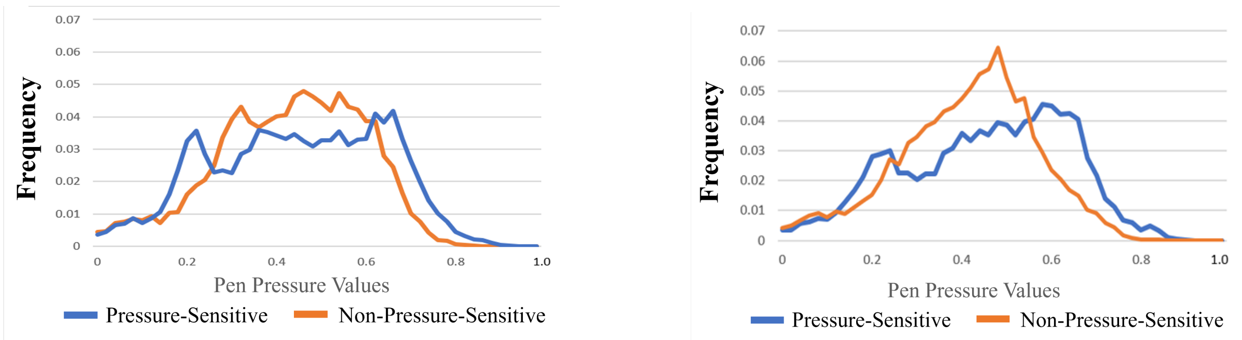
(a) Pressure-sensitive condition

(b) Non-pressure-sensitive condition

Fig. 5: Accuracy rate per participant under each condition.

4.4. *Average Distribution of Pen Pressure*

Figures 6a, and 6b present the distribution of pen pressure values across multiplication problems, and division problems, respectively, under both the pressure-sensitive and non-pressure-sensitive conditions. The results show that in the pressure-sensitive condition, pen pressure values are more widely distributed, reflecting greater variation in stroke intensity across participants. This suggests that participants may have consciously controlled their pen pressure as a means of organizing auxiliary information during the calculation process. In contrast, the non-pressure-sensitive condition shows a more concentrated distribution around a single value, with most pen pressure values falling within a narrow range. Notably, Figure 6b illustrates that during division problems in the non-pressure-sensitive condition, pen pressure values are especially concentrated near a single level, compared to the pressure-sensitive condition.



(a) Multiplication problems

(b) Division problems

Fig. 6: Distribution of pen pressure values under the pressure-sensitive and non-pressure-sensitive conditions. (a) Multiplication problems. (b) Division problems. The horizontal axis represents pen pressure values (ranging from 0 to 1), while the vertical axis indicates the frequency of each value.

5. Discussion

5.1. *Effect of Pen Pressure Sensitivity Across Arithmetic Operations*

The experimental results showed no difference in accuracy between the pressure-sensitive and non-pressure-sensitive conditions for addition, subtraction, and multiplication, but a difference was observed for division. Furthermore, an analysis of individual participants' accuracy rates revealed that while the difference between multiplication

Table 1: The Proportions of Each Error Type

	pressure-sensitive condition	non-pressure-sensitive condition
Calculation Errors	0.48	0.32
Carrying/Borrowing Mistakes	0.30	0.25
Misreading	0.15	0.25
Other	0.07	0.18

and division accuracy was minimal in the pressure-sensitive condition, a larger gap was observed in the non-pressure-sensitive condition. This contrast suggests that the absence of pressure sensitivity may have a greater negative impact on more complex operations such as division. These results partially support the hypothesis that varying stroke darkness through pen pressure improves calculation accuracy, particularly for complex operations like division.

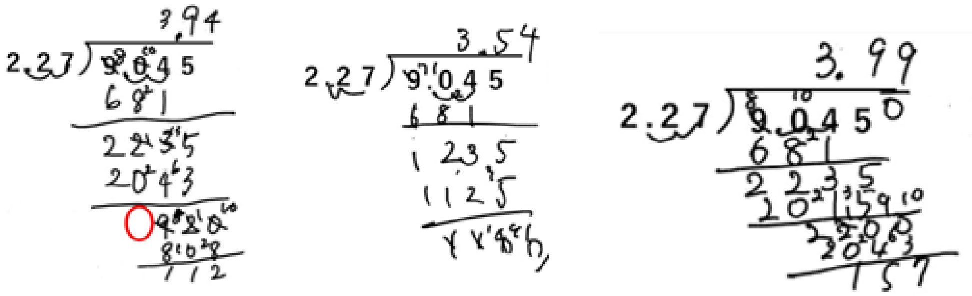
Regarding the distribution of pressure values, the non-pressure-sensitive condition showed a more concentrated distribution than the pressure-sensitive condition. This suggests that participants were unable to adjust their writing pressure according to the content, which may have reduced their motivation to control pen pressure.

5.2. Classification of Incorrect Answers

To investigate the impact of the absence of pressure sensitivity on the nature of incorrect answers, we classified the errors into the following four categories:

- Calculation Errors: The numbers used in the calculation were correct, but the final answer was incorrect.
- Carrying/Borrowing Mistakes: Errors caused by excessive or omitted carrying or borrowing.
- Misreading: Misuse of unintended numbers in the calculation,
- Other: incorrect digit placement, or errors due to unknown causes.

The classification was performed manually by the researchers based on written responses. Based on this classification, the proportions of each error type under the two conditions are shown in Table 1. The results indicate that the most common error type in both conditions was calculation errors. The second most frequent errors were carrying/borrowing mistakes in the pressure-sensitive condition, and a combination of carrying/borrowing mistakes and misreading in the non-pressure-sensitive condition. Examples of errors observed under the non-pressure-sensitive condition are shown in Figures 7(a), 7(b), and 7(c).

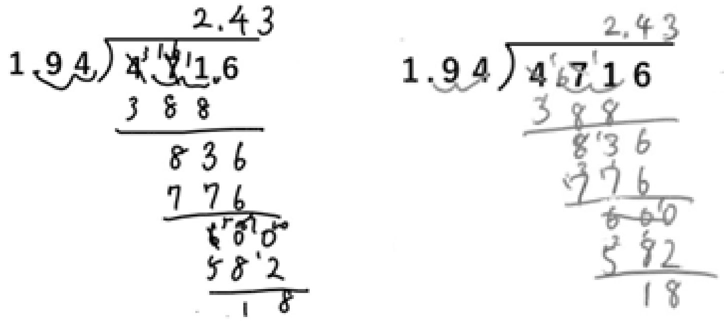


(a) Calculation Mistake (b) Carrying and Borrowing Errors (c) Misreading

Fig. 7: Examples of errors observed under the non-pressure-sensitive condition.

In Figure 7(a), the result of subtracting 204.3 from 223.5, which should have been 19.2, was incorrectly calculated as 9.2. The respondent made a subtraction mistake despite having written down the carry operation. In Figure 7(b), the respondent erroneously carried down the hundreds digit of 904.5. The proportion of carrying mistakes among all error types was 0.07 in the pressure-sensitive condition and 0.14 in the non-pressure-sensitive condition, suggesting that the lack of darkness variation may have increased the likelihood of misrecognition during calculations. In Figure 7(c), a mistake occurred during the multiplication of the first decimal digit of the quotient. The correct result of multiplying 2.27 by 9 should have been 20.43, but the respondent answered 20.15. This error likely resulted from misreading the digit 7, possibly due to its visual similarity to the underlying problem text in the absence of stroke darkness variation. These examples suggest that the absence of pressure-induced darkness may negatively affect the calculation process. To address this, we plan to adjust the darkness range in the pressure-sensitive condition and revalidate the findings in future experiments.

Figure 8 shows solutions to the same problem under the two conditions. In Figure 8(a), under the non-pressure-sensitive condition, the cancellation line drawn over the numbers is also hard to distinguish. In contrast, Figure 8(b), under the pressure-sensitive condition, shows that the cancellation line is drawn more lightly, making it easier to distinguish the original digits in the problem. This difference in visibility may have contributed to the observed difference in accuracy between the two conditions. Based on these errors, it is possible that the absence of pressure sensitivity affected accuracy, as long division often involves auxiliary digits such as carried or borrowed numbers, as well as other handwritten calculation marks. Therefore, pen pressure induced darkness in digital handwriting appears to play an important role in improving calculation accuracy and reducing errors caused by misreading.



(a) Non-pressure-sensitive condition (b) Pressure-sensitive condition

Fig. 8: Examples of carrying and borrowing notes.

Finally, we discuss the limitations and future directions of this study. In the pressure-sensitive condition of this experiment, participants were not able to fully represent variations in stroke darkness. One possible reason is that the range of participants' pen pressure was not taken into account. As Yin et al. [18] noted, the natural range of pressure used in drawing and writing is concentrated. Therefore, future experiments will aim to recalibrate the mapping between pen pressure and stroke darkness enabling users to represent clearer variations in stroke darkness with less physical effort.

The pressure induced darkness examined in this study has potential applications beyond manual calculations. For example, in puzzle-solving, users may temporarily write down tentative values, while in geometry problems, they may emphasize important information by writing more darkly. These behaviors may be related to affective states, such as confidence or uncertainty, that emerge during problem-solving.

These findings suggest that pen pressure is not merely a technical feature of digital pens but an integral part of cognitive expression in educational contexts. As such, supporting pressure sensitive input may enhance the effectiveness of digital learning environments.

6. Conclusion

This study hypothesized that calculation accuracy would be higher in the condition where stroke darkness varies with pen pressure than in the condition where stroke darkness remains constant. To test this hypothesis, we conducted an experiment in which participants solved arithmetic problems using a digital pen. We examined the effects of pressure-induced stroke darkness on accuracy, calculation time, and pressure distribution. The results showed that, in division problems, the pressure-sensitive condition led to a higher accuracy rate and shorter response times. These findings suggest that variable stroke darkness may help reduce calculation errors, possibly by improving the visual clarity of handwritten notes. In particular, the results and error analyses suggest that the absence of pressure sensitivity may hinder users from clearly distinguishing auxiliary digits—such as carried or borrowed numbers—and other handwritten calculation marks, thereby increasing the likelihood of misreading and miscalculation. However, several limitations were identified during the experiment, including individual differences in participants' calculation skills and suboptimal mapping between pen pressure and stroke darkness.

In future work, we plan to conduct a within-subjects experiment in which the same participants complete problems under both pressure-sensitive and non-pressure-sensitive conditions. This design will allow us to more clearly evaluate the differences in accuracy and calculation time. Additionally, since the intended target users of this system are elementary and junior high school students, further experiments will also be conducted with participants in this age group to investigate age-specific effects.

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