CalcQuest: A Gamified Abacus Learning Support System for Enhancing Operational Proficiency

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Abstract. Abacus learning improves calculation speed, memory retention, and concentration. However, learners often encounter difficulties with specific operations, leading to reduced learning efficiency and repetitive practice of similar operations, which can cause mental fatigue and a decline in motivation. To address these challenges, this study proposes CalcQuest, a gamified learning support system designed to help learners overcome operational weaknesses through structured and engaging practice. CalcQuest incorporates an abacus board recognition system using a document camera with AR markers, a mechanism for detecting operational weaknesses and generating personalized problems, and a gamified user interface to integrate these components. Through a two-week exploratory study with six novice learners, we compared CalcQuest with a baseline system in terms of calculation accuracy, calculation speed, and observed behavioral trends. The results suggest the potential of integrating personalized feedback and gamification to support abacus learning.

Keywords: Abacus · Education · Learning Support · Gamification.

1 Introduction

The abacus (*Soroban*) is a traditional calculating tool to represent numbers and perform arithmetic operations by sliding beads along rods (Figure 1). Beyond its primary function as a calculator, the abacus is widely recognized for its educational benefits, including calculation speed, memory retention, and concentration [1, 2, 8, 15, 18, 19, 10, 20]. In recent years, the widespread adoption of calculators and computers has reduced the practical need for the abacus. Nevertheless, abacus learning remains popular, not only in Japan but also in many countries worldwide.

One of the key challenges in abacus learning is addressing "operational weaknesses," defined as recurrent procedural errors such as the omission of complementary addition or incorrect carry operations. Learners often encounter difficulties with specific operations, leading to repeated errors that hinder progress and reduce learning efficiency. Furthermore, repetitive practice of similar operations can result in mental fatigue, which may negatively affect learner motivation. Most existing abacus learning support systems do not explicitly focus on the

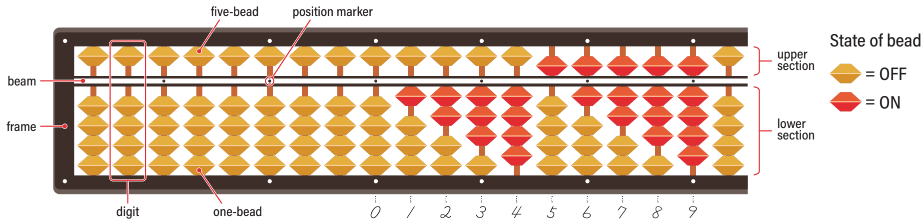


Fig. 1. Components and number representation of the abacus.

identification of such operational weaknesses and instead rely on learners or instructors to manually diagnose these difficulties [3].

To address these challenges, we propose a novel abacus learning support system called "CalcQuest" as shown in Figure 2. This system introduces an approach to identifying learners' operational weaknesses by leveraging our prior work, an abacus input value estimation method that utilizes a document camera as a sensor [12]. Based on the identified weaknesses, the system automatically generates personalized calculation problems designed to help learners naturally overcome their difficulties and improve proficiency. These problems are seamlessly integrated into a gamified interface, encouraging learners to engage with the exercises in a fun and motivating way, thereby fostering sustained learning and mastery.

This paper presents the design, implementation, and evaluation of CalcQuest. Through a two-week exploratory study with six novice university students, we examined the use of CalcQuest in comparison with a baseline system and observed trends related to operational weaknesses, calculation speed, accuracy, and learner behavior. The results suggest that integrating personalized problem generation with gamification may support learners in addressing operational weaknesses while sustaining engagement during abacus practice. By focusing on both operational challenges and mental fatigue, CalcQuest demonstrates the potential of gamified learning support for abacus education.

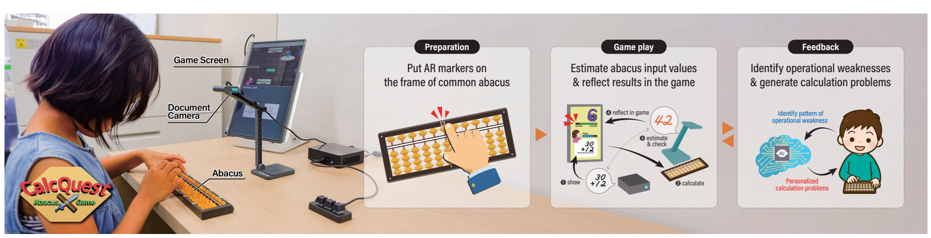


Fig. 2. Overview of CalcQuest, a gamified abacus learning support system.

2 Basic Knowledge of Abacus

An abacus is an assistive tool for various calculations such as the four arithmetic operations by expressing numbers with the positions of five beads which can be moved vertically. This section provides summary of the preliminary knowledge of the abacus.

2.1 Numerical Representation Using Abacus

First, the components of the abacus are shown in Figure 1 (left). A *digit* corresponds to one digit in base 10, and the placement of five beads can represent numbers from "`0` $\sim$ `9`." Each *digit* is divided into an upper and lower section by a *beam*, and the single bead in the upper section (`five-bead`) represents the base-10 number "`5`," while the four beads in the lower section (`one-beads`) represent base-10 numbers "`1`" each. A specific example of numerical representation is shown in Figure 1 (right). There is a space half the height of the beads in both the upper and lower sections, and the state of each bead is represented by moving the beads up and down. In the upper section, the bead in the raised position represents OFF (`0`), while the lowered position represents ON (`5`); conversely, in the lower section, the raised position represents ON (`1`), and the lowered position represents OFF (`0`). The sum of the beads in the same digit (the total of the numerical values represented by the beads in the ON state) represents the value of that digit. The *position marker* in Figure 1 is indicated on the beam every three digits and is used as a marker to determine the ones place. The digits to the right of the determined position marker are used to represent decimals.

2.2 Calculation Methods with the Abacus

Calculations using the abacus are characterized by the extensive use of complementary combinations of 5 and 10. Specifically, there are three types of manipulations. In the following, we explain the procedure for each manipulation with addition as an example, but subtraction can also be represented in a similar manner by performing the inverse manipulation of it.

First, the **Calculations involving either one-beads or five-bead** is the simplest manipulation, which can be completed by moving either `one-beads` or `five-bead`. The following are examples of addition. First, for the calculation of `1` + `2`, starting from the state with only one `one-bead` raised (`1`), a manipulation to raise two more `one-beads` (+2) can be performed, resulting in the state representing `3`. For the calculation of `3` + `5`, with three `one-beads` raised (`3`), the manipulation of lowering the `five-bead` (+5) can be performed, resulting in the state representing `8`.

Second, the **Calculations involving one-beads and five-bead** requires simultaneous movement of `one-beads` and `five-bead`. Specifically, it corresponds to the manipulation where the state changes from `0` $\sim$ `4` to `5` $\sim$ `9` (or the reverse). The following are examples of addition. The calculation of `1` + `6` can be obtained by combining manipulation (1), adding `6` (i.e., `5` and `1`) to the state with one bead raised (1), resulting in the calculated result of 7. On the other hand, the calculation of $2 + 4$ requires adding 4 to the state with two beads raised (2), but since there are only four one-beads per digit, this calculation cannot be represented by the combination of only one-beads. Therefore, the concept of the complement of 5 is introduced. Since 4 can be expressed as $5 - 1$, performing the manipulations of "subtracting 1 (lowering one one-bead)" and "adding 5 (lowering the five-bead)" simultaneously from the current input value of 2 results in the calculated result of $2 + 4$, which is 6.

Third, the **Calculations involving two digits (carrying and borrowing)** requires the movement of beads over two digits. Specifically, it corresponds to the manipulation where the state changes from $0 \sim 9$, which can be represented in one digit, to a number of 10 or greater (or the reverse), i.e., carrying or borrowing. The following are examples of addition. In the calculation of $3 + 8$, 8 will be added to the state with three beads raised (3), however since it cannot be represented within a single digit, the concept of the complement of 10 is introduced. Since 8 can be expressed as $10 - 2$, performing the manipulations of "subtracting 2" and "adding 10" simultaneously from the current input value of 3 results in the calculated result of $3 + 8$, which is 11. In addition, there are cases where the complement of 5 must also be considered. For example, in the calculation of $6 + 8$, although 8 requires considering the complement of 10 as mentioned above, and subtracting 2 from the one's place, subtracting 2 from 6 requires considering the complement of 5 ($5 - 3$). Thus, to obtain the calculated result of $6 + 8$, which is 14, it is necessary to perform the three manipulations of "adding 3", "subtracting 5", and "adding 10" simultaneously.

3 Related Work

There are several existing works for supporting abacus learning. Arakawa *et al.* [3] proposed a Learning Management System (LMS) for abacus education, managing learning software such as flash mental arithmetic, reading aloud arithmetic, and quick-view arithmetic on the LMS, and combining it with individual grades and learning progress to enable learning anywhere with a PC equipped with the software. Kitagawa *et al.*[3] proposed an abacus learning support system consisting of a board estimation system using a camera and a projection mapping system that overlays images on the beads to convey manipulation methods. The system estimates input values on the abacus using an RGB camera placed at the backside of a transparent table. Based on estimated results, the projector provides various instructions about abacus manipulations on the table or on the beads of the abacus. There are also approaches to support abacus learning by reproducing the abacus on the screens of smartphones and tablet devices. Saito *et al.* [13] proposed an electronic abacus feature as a plugin for a learning support system designed for smartphones. By reproducing the abacus on the screen, basic abacus manipulations can be performed, and the process of calculation using

[3] This paper is published only in Japanese: http://www.interaction-ipsj.org/proceedings/2022/data/pdf/6D04.pdf

the electronic abacus can also be displayed as a formula. Baharudin *et al.* [5] proposed an interactive abacus learning application, which was implemented as PC software, for beginners. Digika offers a service called *SoroTouch* [14], which provides mental arithmetic learning instruction based on the abacus UI and manipulation methods. The system reproduces an abacus-like interface on tablet devices and adopts a calculation method that operates buttons corresponding to beads with both hands. Tokuda *et al.* [16] proposed a method for estimating abacus learners' performance using matrix factorization on student-generated learning data with the Sorotouch app.

Our previous work proposed the method to recognize input values on the abacus in real-time using a document camera as a sensor [12], and also developed an abacus learning support system using a commercially available abacus and a table-top interface to provide coaching content based on abacus input value estimation [11]. The system presents calculation problems on a table-top interface and shows instructions near the corresponding digits where calculation mistakes occur. In addition to addressing cognitive difficulties, sustaining learner motivation is a critical challenge in abacus learning due to the repetitive nature of procedural practice.

To improve the skills of abacus learners, it is essential to identify weaknesses or errors in their calculation processes and provide tailored guidance accordingly. However, these processes have traditionally relied on direct instruction from lecturers, presenting a challenge in realizing ICT-based learning support systems. Existing abacus learning support systems have focused primarily on fundamental instruction for abacus operations and calculation processes. Few systems have incorporated functionalities to identify and address learners' individual weaknesses. Additionally, while gamification has been explored as a means to enhance learning motivation, its application to abacus-specific learning remains limited. This study aims to provide tailored learning support to overcome these difficulties by detecting operational weaknesses of each learner using the abacus operation sensing based on our previous work [12]. Moreover, the integration of gamification elements seeks to enhance learner engagement and motivation, addressing the psychological challenges of repetitive practice.

In recent years, gamification and game-based learning have been widely explored as effective approaches for enhancing learner motivation and engagement in educational contexts. Prior studies have shown that embedding learning tasks directly into core gameplay mechanics, rather than presenting them as auxiliary quizzes, leads to higher engagement and improved learning outcomes. Habgood and Ainsworth demonstrated that intrinsically integrated educational games, in which solving academic problems directly advances in-game progress (e.g., defeating enemies), significantly outperform extrinsically integrated designs in both learning gains and time-on-task [6]. RPG-inspired learning environments have also been shown to be effective in mathematics education. Turn-based battle metaphors, where learners solve problems to attack opponents or avoid damage, provide immediate and meaningful feedback that sustains engagement and supports persistence. Such designs have been reported to be particularly effective

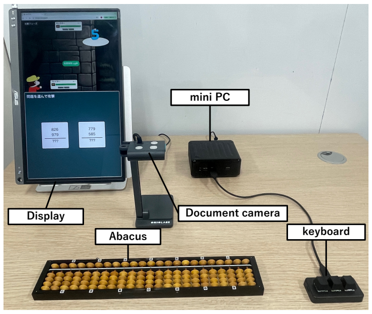
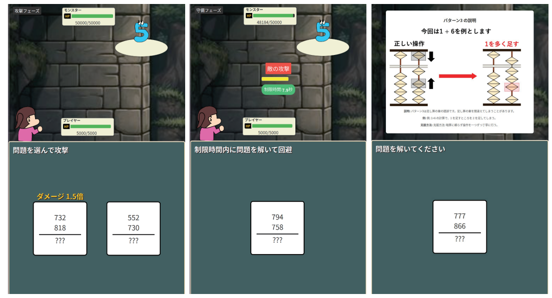


Fig. 3. CalcQuest System Setup.



(a) Attack Phase (P_A) (b) Defense Phase (P_D) (c) Review Phase (P_R)

Fig. 4. CalcQuest Interfaces.

for novice learners and those with lower initial performance, as they frame repeated practice as goal-oriented and enjoyable activities rather than monotonous drills [7, 4]. Furthermore, recent research highlights the importance of learner autonomy in gamified systems. Allowing learners to voluntarily select more challenging tasks, especially when accompanied by higher in-game rewards, has been shown to increase intrinsic motivation. Studies on self-selected difficulty indicate that learners are more willing to engage with challenging problems when they perceive the challenge as a choice rather than an obligation [9, 17]. These findings suggest that gamification designs that positively reinforce voluntary engagement with difficult tasks can effectively promote learning behaviors, particularly in domains that require repeated procedural practice such as arithmetic learning.

4 CalcQuest

CalcQuest is a novel abacus learning support system designed to address operational weaknesses and improve learning efficiency by reducing learners' mental fatigue and promoting sustained motivation through gamified elements that make the learning process enjoyable and engaging, as shown in Figure 3 and Figure 4. It features two core functionalities: identifying operational weaknesses from calculation logs to enhance proficiency, and providing gamified learning materials to mitigate mental fatigue and foster sustained engagement. The following sections delve into the details of each functionality.

4.1 Functionality for Enhancing Operational Proficiency

Definition of Operational Weaknesses Operational weaknesses of abacus refer to specific errors that learners repeatedly encounter during calculations. Based on an analysis of common errors faced by learners, we originally categorize these weaknesses into the following six patterns.

First, **Pattern 1 (*omission of addition*)** refers to cases where required addition operations are not performed, e.g., skipping "add 3" operation in the calculation of $6 + 8$. **Pattern 2 (*omission of subtraction*)** refers to cases where required subtraction steps are not performed, which is the inverse of Pattern 1. Next, **Pattern 3 (*errors in addition amount*)** refers to cases where an incorrect value is added. For example, in the calculation of $1 + 6$, adding 1 more than necessary represents this pattern. **Pattern 4 (*errors in subtraction amount*)** refers to cases where an incorrect value is subtracted, which is the inverse of Pattern 3. Then, **Pattern 5 (*confusion of five- and one-beads*)** occur when different types of beads are operated. For example, in the calculation of $3 + 5$, mistakenly adding 10 instead of 5 categorizes this pattern. Finally, **Pattern 6 (*reversal of addition and subtraction*)** refers to cases where addition is mistakenly performed instead of subtraction, or vice versa. For example, in the calculation of $8 + 3$, incorrectly subtracting 7 by misinterpreting the complement of 10 and subtracting 3 instead represents this pattern.

Method for Identifying Operational Weaknesses The operational weaknesses are identified based on the tendency of the repeative errors. It suggests that the learner may misunderstand or may have forgotten the specific abacus operation procedures. CalcQuest adopts a method to identify the operational weakness pattern based on calculating the digit-wise differences between the learner's answer and the correct answer of the given calculation problems when the learner's answer is wrong. Specifically, the difference values for each digit between leaner's answer and correct answer are calculated to estimate the possible reasons of error. Accumulating these estimations, the frequent patterns of operational weaknesses can be identified from the six predefined patterns mentioned above. For example, consider the calculation "$6 + 8$," where the recognized result is 11. In this case, the correct answer is 14, resulting in a difference value of -3. This difference value of -3 indicates that the operation to "add 3" was omitted. This can be identified as Pattern 1 of the operational weaknesses (omission of addition).

Method for Detecting Operational Weaknesses in Multi-Digit Calculations In multi-digit calculations, operations such as carrying and borrowing can influence other digits. As a specific example, consider the calculation "$12 + 48$," where the result is recognized as 70. The method for detecting operational weaknesses in this case is as follows: First, in multi-digit calculations, errors are estimated sequentially from the highest digit. In this case, the recognized result for the tens digit is 7, while the correct value is 6, resulting in a difference value of 1. Based on this difference, the system verifies whether the carrying operation affecting the calculation "$1 + 4$" was performed correctly. The program refers to the calculation result of the lower digit, "$2 + 8$," to determine whether the carrying operation was appropriately executed. The difference value of 1 suggests two possible errors: (1) the omission of the operation to "subtract 1" during the calculation "$1 + 4$," or (2) the correct execution of "$1 + 4$," but an error in the calculation "$2 + 8$," where the operation to lift one bead ($+10$) in the leftmost column was mistakenly performed as lifting two beads ($+20$). By analyzing these difference values, the system can detect Pattern 2 (omission of subtraction) and

Pattern 3 (errors in addition amount) as operational weaknesses. This method is not limited to two-digit calculations and can also be applied to three-digit or higher calculations. Even as the number of digits increases, the system can break down the calculation into individual digits and verify the results to detect operational weaknesses using the same procedure. Detected operational weaknesses are recorded in the database according to their corresponding patterns. Even when multiple operational weaknesses are identified simultaneously, each is independently detected and recorded appropriately. Additionally, if an error does not match any of the predefined six patterns, it is categorized and recorded as "Other."

Problem Generation Method for Enhancing Operational Proficiency Based on the detection results of operational weakness patterns, problems containing the identified weaknesses are generated. Specifically, as a particular pattern is repeatedly detected, the detection count for that pattern increases. When the detection count exceeds five, the system flags it as an operational weakness. Once flagged, problems containing the corresponding operational weakness are prioritized for presentation. When a learner answers a problem containing the flagged operational weakness correctly, the accumulated detection count for that pattern decreases by one. This process continues, and when the detection count falls to three or below, the weakness is considered resolved, and the flag is removed. Once the flag is removed, problems containing that operational weakness are no longer presented. However, if the same pattern is detected again and its detection count exceeds five, the operational weakness is flagged once more, and problems containing it are prioritized following the same procedure. If no operational weakness patterns are detected, random problems are generated instead.

4.2 Functionality of Gamified Learning Materials

The gamified learning materials in CalcQuest were designed based on prior findings in educational gamification and game-based learning research. In particular, the system adopts an RPG-style turn-based battle metaphor, in which solving calculation problems directly affects the state of the game, such as attacking an enemy or avoiding damage. This design aims to intrinsically integrate learning activities into gameplay so that calculation itself becomes a meaningful in-game action rather than an auxiliary task [6]. The overall system flow is shown in Figure 5. The gameplay is structured into four sequential phases: Attack, Defense, Judgment, and Review.

First is the **Attack Phase** ($\mathrm{P_A}$) as shown in Figure 4 (a). At the top of the screen, the enemy's illustration and hit points (HP_E) are displayed, while the player's illustration and hit points (HP_P) are shown in the center. Two calculation problems of varying difficulty are presented at the bottom of the screen during this phase. The problem on the left includes the player's operational weaknesses, while the problem on the right is a randomly generated problem. The player selects and solves one of the two problems. To encourage engagement

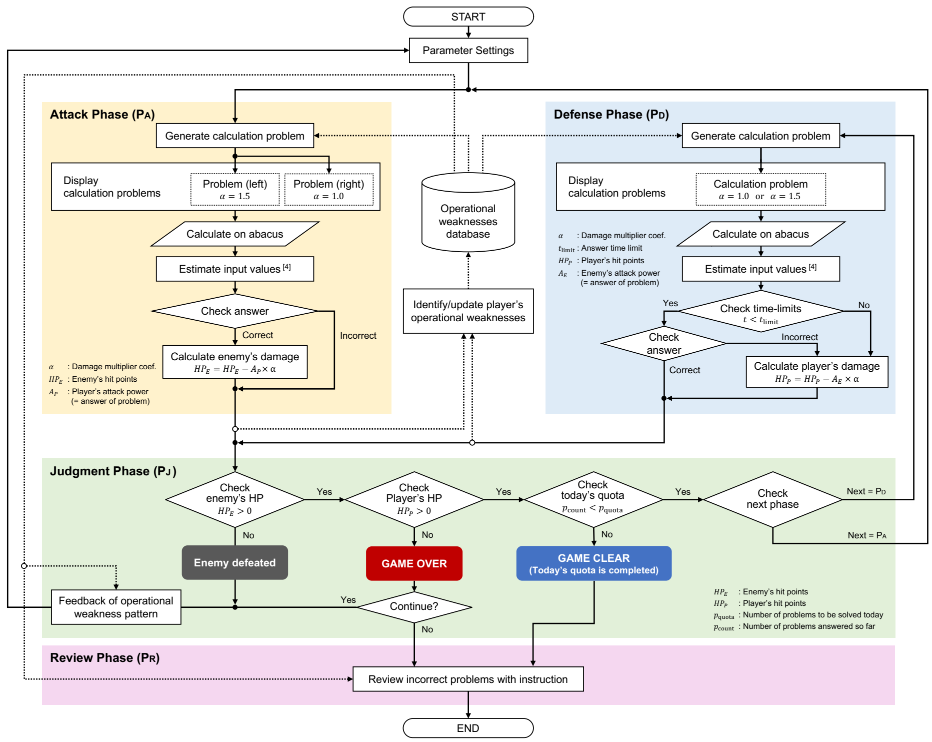


Fig. 5. System flow of the gamified abacus learning support system.

with operational weaknesses, the damage dealt to the enemy is adjusted based on the selected problem. When the learner correctly solves a problem containing operational weaknesses, a higher damage multiplier ($\alpha = 1.5$) is applied, resulting in greater damage. In contrast, solving a randomly generated problem applies a standard multiplier ($\alpha = 1.0$). This design allows learners to voluntarily choose whether to engage with more challenging, weakness-related problems, rather than forcing repeated exposure to them. Such self-selected challenge-taking behavior has been shown to play a crucial role in sustaining intrinsic motivation in gamified learning environments, particularly when higher rewards are associated with more challenging tasks [9, 17]. The system automatically infers which problem was selected by comparing the calculation result with the correct answers of both problems. If the player's answer is correct, damage is dealt to the enemy according to $A_P \times \alpha$, where the answer of the solved problem is used as the player's attack power A_P. If the answer is incorrect, no damage is dealt to the enemy.

Next is the **Defense Phase** ($\mathrm{P_D}$) as shown in Figure 4 (b). At the top of the screen, the enemy's illustration and hit points (HP_E) are displayed, with the player's illustration and hit points (HP_P) in the center. A single calculation problem is shown at the bottom of the screen. A bar between the enemy and the player represents the time-limit (t_{limit}). During the Defense Phase, the player is presented with a problem that includes their operational weaknesses. If no weaknesses have been detected, a random problem is presented instead. If the player answers the problem correctly within the time limit, the enemy's attack is avoided. However, if the time limit expires or the answer is incorrect, the player takes damage ($A_E \times \alpha$, the answer of solved problem will be enemy's attack power A_E).

Judgment Phase ($\mathrm{P_J}$) checks status of the game. In this phase. the remaining health points of the player (HP_P) and the enemy (HP_E) are evaluated, and the next phase is determined. If the player's health points reach zero ($HP_P \leq 0$), the game enters a *Game Over* state, and the player is prompted to decide whether to continue the game. If the player chooses to continue, a new game begins with updated parameters. If the player chooses not to continue, the game is finished. If the number of answered problems (p_{count}) reaches today's quota (p_{quota}), the game enters a *Game Clear* state, and finishes. A single round consists of the Attack Phase ($\mathrm{P_A}$), followed by the Judgment Phase ($\mathrm{P_J}$), the Defense Phase ($\mathrm{P_D}$), and another Judgment Phase ($\mathrm{P_J}$), and it will repeat multiple rounds until the end of the game.

After finishing the game, **Review Phase** ($\mathrm{P_R}$) as shown in Figure 4 (c) provides the problems they answered incorrectly during the game, and the player revisits and solves them. Each review problem will be provided with explanations of the correspond operational weakness pattern at the top of the screen.

5 Evaluation and Discussion

5.1 Experiment and Evaluation Method

In this experiment, we evaluated the proposed system, CalcQuest, to enhance abacus proficiency. The purpose of the experiment was to verify the effectiveness of features such as operational weakness detection, problem generation, and UI feedback incorporating gamification elements in overcoming operational weaknesses and improving abacus proficiency. This study was conducted with the approval of the "Research Ethics Committee for Studies Involving Human Subjects" at Nara Institute of Science and Technology (approval No.: 2022-I-63-1).

The experiment was conducted over 14 days, with the proposed system installed to university campus at Nara Institute of Science and Technology. The participants were six graduate students (gender: male 5, female 1; age: 22–25) who had no prior experience in learning abacus. Before the experiment, the purpose of the study, instructions for using the system, and the basics of abacus operation were explained to them. Then, a pre-test was conducted, and the participants were divided into the following two groups (CalcQuest: n=3, Baseline: n=3) based on their scores to ensure balance between the groups. The difficulty level of calculation problems is set as three-digit two-term problems based on their scores for evaluating the improvement of participants' calculation abilities. All participants solve 50 calculation problems using the abacus every day ($p_{\text{quota}} = 50$). After the experiment, short semi-structured interviews (5–10 minutes) were conducted. Responses were recorded and qualitatively analyzed.

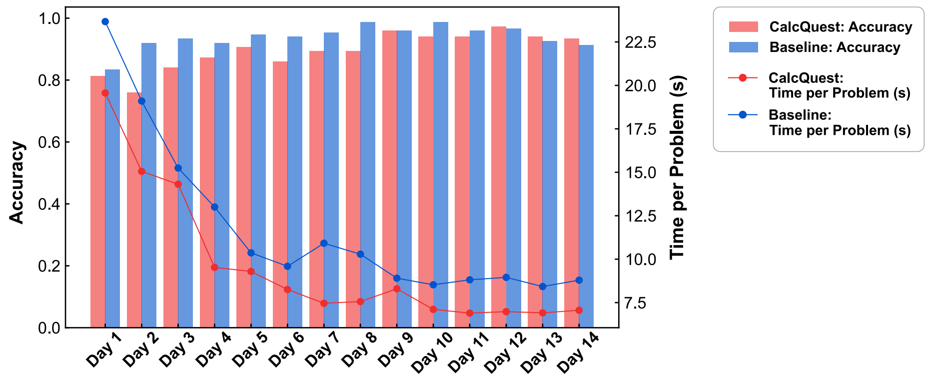


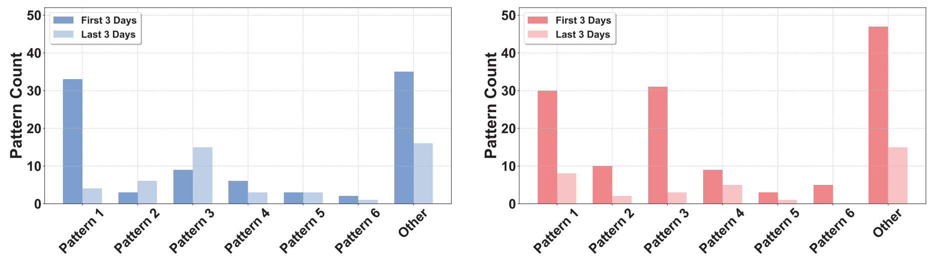
Fig. 6. Daily trends in accuracy rates and calculation time per problem for CalcQuest and Baseline groups.

CalcQuest group is the experimental group, they use the proposed system with all functionalities as described in Section 4. The time-limit for each problem (t_{limit}) was set to 10 seconds, regardless of the participants' skill levels. Each time they reach *Game Over*, *Game Clear*, and *Enemy defeated*, participants can review the summary of learning (the number of correct answers, incorrect answers, and elapsed time), and explanations of the operational weakness patterns corresponding to the incorrect answers. At the review phase, participants can view and solve problems that were not correctly answered by revisiting the explanations of the operational weakness patterns shown at the top of the screen. (Figure 4 (c)).

Baseline group is control group, they use the basic system same as the CalcQuest group, but proposed functionalities (operational weakness detection, and gamified learning materials) are not included. After finishing today's quota (p_{quota}), the system automatically check the answers, and shows the summary of today's study (the number of correct answers, incorrect answers, and elapsed time). At the review phase (P_R), participants can solve problems which were not correctly answered, but no explanation about operational weakness pattern will be provided. This baseline configuration was designed as a minimal comparison condition and does not isolate individual system components.

5.2 Calculation Accuracy and Calculation Speed

From the results shown in Figure 6, the CalcQuest group exhibited lower accuracy rates in the first half of the experiment but tended to surpass the Baseline group in the latter half. Possible reasons for the lower accuracy rates in the early phase for the CalcQuest group include pressure caused by the time limit as a game element, which may have led to increased errors due to rushing, and frequent exposure to problems containing operational weaknesses, which could have suppressed accuracy rates at the initial stage. On the other hand, the improved accuracy rates observed in the latter half may be related to continued



(a) CalcQuest group (b) Baseline group

Fig. 7. Operational weakness patterns of each group detected at the first and last three days of the experiment.

engagement with weakness-focused practice and the motivational features of the game scenario. These observations suggest trends toward improvements in learning performance, reflected in increases in both accuracy rates and calculation speed. In contrast, the Baseline group recorded the highest accuracy rates around the midpoint of the experiment but showed a decline in the latter half. According to interviews, some participants (P5, P6) mentioned "*losing interest in the latter half*" and "*feeling like it was just repetitive work*," suggesting that the monotonous learning environment may have led to reduced engagement. Additionally, comments such as "*I couldn't maintain focus*" and "*My calculation errors increased*" were reported, which may have been associated with the observed decline in accuracy rates in the later stages. In the CalcQuest group, participants provided feedback such as "*The game scenario and the operational weakness-overcoming feature were motivating*" (P2, P3). Furthermore, one participant suggested that "*if there was a mechanism to increase the speed during the attack phase, it would further boost motivation*" (P2), indicating potential areas for future improvement in supporting learner engagement. These qualitative observations suggest that the game elements in CalcQuest may have contributed to sustaining engagement during the learning process.

Additionally, in terms of calculation speed per problem, the CalcQuest group consistently solved problems faster than the Baseline group, with the observed difference reaching approximately two seconds by the 14th day. This trend may be related to the requirement for quick responses under the time limit imposed in CalcQuest. In contrast, the Baseline group, which did not include a time limit, was able to solve problems more slowly and accurately. As a result, although the Baseline group gradually increased their calculation speed, they did not exceed the performance observed in the CalcQuest group.

5.3 Changes in Patterns of Operational Weaknesses

Figure 7 shows the total number of detected operational weaknesses in each group during the first and last three days of the experiment. In the CalcQuest group, a decreasing trend in detected operational weaknesses was observed, with particularly notable reductions in Patterns 1 and 3. This result suggests that the feedback functionality in CalcQuest may have helped reduce the frequency of repeated errors. Specifically, the feedback provided during the review phase may have supported learners in reflecting on their mistakes and adjusting their calculation processes. Due to the experimental scenario, participants in the CalcQuest group were exposed to a larger number of problems containing operational weaknesses compared to those in the Baseline group. While such exposure would typically be expected to increase the number of detected weaknesses, a decrease was observed over time. This observation suggests that the weakness-focused practice and feedback mechanisms in CalcQuest may have contributed to reducing repeated operational errors. In contrast, the Baseline group exhibited an increasing trend in the detection of Pattern 3 during the latter half of the experiment. This trend suggests that operational weaknesses may not have been sufficiently addressed in the absence of explicit feedback targeting specific error patterns. Although the Baseline group also included a review phase, the lack of targeted feedback on operational weaknesses may have increased the tendency for learners to repeat similar errors. These observations highlight the potential importance of feedback that not only allows learners to retry problems but also supports understanding of the underlying causes of errors.

Furthermore, both groups showed a high frequency of operations classified as "Other," indicating the need to reevaluate the current definitions of operational weaknesses and consider the inclusion of additional patterns in future work. In the CalcQuest group, the selection rate for problems containing operational weaknesses was 100%. This observation suggests that the damage multiplier mechanism may have encouraged learners to select weakness-related problems, thereby promoting engagement with challenging operations.

5.4 Limitations

This study has several limitations that should be considered when interpreting the results. First, the sample size was small, consisting of six novice participants, which limits the generalizability of the findings. The study was designed as an exploratory investigation, and the observed results should be interpreted as indicative trends rather than conclusive evidence. Second, the experimental period was limited to two weeks. While short-term changes in calculation performance and learner behavior were observed, the current study does not assess long-term retention, transfer of skills, or sustained motivation. Longer-term studies are required to evaluate the enduring effects of the proposed system. Third, the current experimental design does not isolate the individual contributions of personalized problem generation, gamification elements, and practice frequency. As a result, it is not possible to attribute observed effects to specific components of the system. Future work will employ more controlled experimental designs to examine the role of each factor in greater detail. Finally, participants were novice university students, which may introduce sampling bias and limit applicability to other learner populations, such as children or experienced abacus users. Future studies with more diverse participants are necessary to further validate the effectiveness of the proposed approach.

6 Conclusion

This study proposed CalcQuest, a gamified abacus learning support system designed to help learners improve their skills while reducing mental fatigue. The system identifies operational weaknesses and generates personalized problems to address them, supporting learners in overcoming challenges. By incorporating gamification, it aims to support learner engagement and promote continuous skill development in an engaging learning environment. The effectiveness of CalcQuest was explored through a two-week experiment involving novice learners. The results showed trends of improvement in both calculation accuracy and speed, suggesting that personalized problem generation and gamification elements may have contributed to enhanced learning outcomes. Future research will explore large-scale evaluations, long-term impacts, and refinements to weakness detection and problem generation to further investigate the effectiveness of the proposed approach.

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References

1. Amaiwa, S.: The Effects of Abacus Learning on Solving Arithmetic Problems: A Comparative Study of Elementary / Junior High School Students at Upper Level and Inexperienced Students. Journal of the Faculty of Education, Shinshu University **96**, 145–156 (1999)
2. Amaiwa, S., Hatano, G.: Effects of abacus learning on 3rd-graders' performance in paper-and-pencil tests of calculation. Japanese Psychological Research **31**, 161–168 (1989)
3. Arakawa, K., Kawasaki, K., Sawada, K., Futatsuishi, Y., Kakehi, M., Watanabe, I.: Web Learning Support System Development in Abacus Education. In: The journal of the Faculty of Science and Technology, Seikei University. vol. 48, pp. 75–79 (2011)
4. Babazadeh, M., Maffioli, M., Falcade, R.: Transforming Math Anxiety into Engagement: The Impact of RPG-Based Gamification on Middle School Students. In: Proceedings of the 19th European Conference on Games-Based Learning (ECGBL 2025). pp. 54–63 (2025). https://doi.org/10.34190/ecgbl.19.1.4084
5. Baharudin, S., Rias, R.M., Ahmad, M.F.: Designing an interactive abacus learning application for beginners: A prototype. In: 2010 International Conference on User Science and Engineering (i-USEr). pp. 89–92 (2010). https://doi.org/10.1109/IUSER.2010.5716729
6. Habgood, M.P.J., Ainsworth, S.E.: Motivating Children to Learn Effectively: Exploring the Value of Intrinsic Integration in Educational Games. Journal of the Learning Sciences **20**(2), 169–206 (2011). https://doi.org/10.1080/10508406.2010.508029

7. Hieftje, K., Pendergrass, T., Kyriakides, T.C., Gilliam, W.S., Fiellin, L.E.: An Evaluation of an Educational Video Game on Mathematics Achievement in First Grade Students. Technologies **5**(2), 1–8 (2017). https://doi.org/10.3390/technologies5020030
8. Hu, Y., Geng, F., Tao, L., Hu, N., Du, F., Fu, K., Chen, F.: Enhanced White Matter Tracts Integrity in Children With Abacus Training. Human Brain Mapping **32**(1), 10–21 (2011). https://doi.org/10.1002/hbm.20996
9. Lomas, J.D., Koedinger, K.R., Patel, N., Shodhan, S., Poonwala, N., Forlizzi, J.L.: Is Difficulty Overrated?: The Effects of Choice, Novelty and Suspense on Intrinsic Motivation in Educational Games. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). pp. 1028–1039 (2017). https://doi.org/10.1145/3025453.3025638
10. Lu, Y., Li, M., Cui, Z., Wang, L., Hu, Y., Zhou, X.: Transfer Effects of Abacus Training on Cognition. Current Psychology **42**, 6271–6286 (2023). https://doi.org/10.1007/s12144-021-01968-1
11. Matsuda, Y.: A Table-top Interface for Real-time Coaching in Abacus Learning. In: The 10th International Conference on Smart Computing (SmartComp '24). pp. 243–245 (2024). https://doi.org/10.1109/SMARTCOMP61445.2024.00056
12. Matsuda, Y.: Abacus Manipulation Understanding by Behavior Sensing Utilizing Document Camera as a Sensor. International Journal of Activity and Behavior Computing **2024**(1), 1–16 (2024). https://doi.org/10.60401/ijabc.2
13. Saito, K., Sasaki, H., Mizuno, K.: Development of Learning Support Tools using the Mobile Phone. In: Proceedings of Forum on Information Technology. FIT'09, vol. 8, pp. 653–654 (2009)
14. Sorotouch Co., Ltd.: Sorotouch. `https://www.sorotouch.jp/` (2016), (accessed 2026-01-08)
15. Stigler, J.W.: "mental abacus": The effect of abacus training on chinese children's mental calculation. Cognitive Psychology **16**(2), 145–176 (1984). https://doi.org/10.1016/0010-0285(84)90006-9
16. Tokuda, K., Kaschub, D., Ota, T., Hashimoto, Y., Fujiwara, N., Sudo, A.: Prediction of student performance in abacus-based calculation using matrix factorization. In: Adjunct Publication of the 28th ACM Conference on User Modeling, Adaptation and Personalization. pp. 114–118. UMAP '20 Adjunct (2020). https://doi.org/10.1145/3386392.3399309
17. Tyni, J., Bednarik, R., Kahila, J., Tedre, M.: A bird matching game: Difficulty, rewards and intrinsic motivation. International Journal of Serious Games **11**(4), 57–77 (2024). https://doi.org/10.17083/ijsg.v11i4.602
18. Wang, C.: A Review of the Effects of Abacus Training on Cognitive Functions and Neural Systems in Humans. Frontiers in Neuroscience **14**(913), 1–12 (2020). https://doi.org/10.3389/fnins.2020.00913
19. Wang, C., Xu, T., Geng, F., Hu, Y., Wang, Y., Liu, H., Chen, F.: Training on Abacus-Based Mental Calculation Enhances Visuospatial Working Memory in Children. Journal of Neuroscience **39**(33), 6439–6448 (2019). https://doi.org/10.1523/JNEUROSCI.3195-18.2019
20. Xie, Y., Chang, H., Zhang, Y., Wang, C., Zhang, Y., Chen, L., Geng, F., Ku, Y., Menon, V., Chen, F.: Long-term abacus training gains in children are predicted by medial temporal lobe anatomy and circuitry. Developmental Science **27**(4), e13489 (2024). https://doi.org/10.1111/desc.13489