ITS Unplugged: Leapfrogging the Digital Divide for Teaching Numeracy Skills in Underserved Populations

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Abstract
This paper presents an ITS unplugged workflow to support adaptive teaching in numeracy education of underserved populations with a digital divide. The workflow incorporates a school curriculum-based lesson plan and leverages the ITS unplugged as a pedagogical resource for teaching numeracy. The ITS unplugged utilizes computer vision and natural language processing techniques to capture and analyze students' responses to numeracy tasks through photographs. This paper outlines the workflow of the ITS unplugged solution, highlighting the key stages involved. The pedagogical report provides insights derived from numeracy item analysis, enabling teachers to make informed decisions about their teaching and adapt the approach based on the evidence provided by the ITS.

Keywords
ITS unplugged, Numeracy Education, Adaptive Teaching

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1. Introduction

Numeracy skills, which involve understanding, using, and applying mathematical concepts and skills, are essential for success in today's world [1]. However, many underserved populations, such as low-income communities in the Global South, minority groups, and individuals with disabilities, often face significant challenges in developing these skills [2]. As a result, they may need help to perform basic mathematical tasks and encounter barriers to educational and career opportunities [3].

Countries in the Global South face severe challenges in numeracy education and the digital divide. Addressing and improving numeracy instruction in these regions is paramount to fostering educational equity and empowering individuals with essential mathematical skills [3]. Research has shown that a strong foundation in numeracy has far-reaching implications for individuals' academic achievement, employment prospects, and overall socioeconomic development [4]. Therefore, it is imperative to prioritize interventions and policies targeting numeracy education in the Global South, leveraging evidence-based strategies and interventions to ensure effective and inclusive learning opportunities for all students regarding achieving the United Nations' Sustainable Development Goals (SDGs) 4 (i.e., Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all) and 10 (i.e., Reduce inequality within and among countries).

Intelligent Tutoring System (ITS) has emerged as a promising solution to address the issue of low numeracy skills [5, 6]. ITS is an advanced form of computer-based instruction that provides personalized learning experiences to individual learners based on their unique needs and learning path [7]. According to [8], an ITS uses data-driven algorithms to identify learners' strengths and weaknesses and provide tailored feedback and support, enhancing their understanding and retention of mathematical concepts. Despite that, many underserved populations may not have access to the necessary technological devices and internet connectivity required to use traditional ITS systems, which has limited the ability of educators and researchers to leverage the full potential of ITS to enhance numeracy skills in these populations [9, 10].

Recent studies have proposed frameworks for addressing such limitations. Particularly, [11] and [12] advocate using image processing techniques to collect students' handwritten solutions, digitizing and sending them to an ITS, which would generate printable teacher feedback. The idea is that digitizing might be done asynchronously, which enables benefiting from the ITS even when technology is not always available. Additionally, both studies [11, 12], adopt a process-centered focus, which provides valuable contributions to designing unplugged ITS (i.e., those for low-cost devices with resource constrain and connectivity). Nevertheless, research demonstrates that pedagogical aspects are central for designing an ITS [13] and involving and training teachers [5]. As previous studies highlight the particular issues from such technologies [11, 12], there is the need for conceptualizing how to design pedagogy-centered unplugged ITS.

This paper addresses this challenge by presenting a workflow for teaching numeracy skills using a low-tech and offline ITS approach called "ITS unplugged". This study aims to present the big picture of an in-class workflow, providing a method for enhancing the numeracy skills of underserved populations with low or no access to technology.

The ITS unplugged leverages the principles of ITS to provide personalized, data-driven instruction to teachers while eliminating the need for real-time internet connectivity and advanced technological devices. Instead, it utilizes offline resources to leapfrog the digital divide, such as taking photos with low-tech smartphones and handwritten activities to provide tailored instruction to the teachers.

2. Key aspects beyond ITS

2.1. Early Stage of Development in Numeracy

According to Piaget [14], cognitive development occurs through sequential and progressive stages. It implies that children go through distinct stages when acquiring numerical skills in numeracy. The first stage is the Sensorimotor Period, in which children explore the world through their senses and movements during the first two years of life. In this phase, they begin to develop basic notions of quantity and can engage in matching activities. The second stage is the Preoperational, in which children start using symbols and mental representations Between the ages of two and six or seven. In this stage, they acquire the ability to count, typically starting with verbal counting up to 10 and then progressing to more comprehensive counting. The third stage is Concrete Operations. From seven to eleven years old, children begin to think more logically and develop the mental ability to manipulate concrete objects. In this phase, they better understand numerical concepts such as arithmetic. The last stage is Formal Operations. From eleven or twelve years of age, children enter the stage of formal operations, where they can think abstractly and hypothetically. In this stage, operational numerical skills become more complex, and students can deal with more abstract mathematical concepts.

Assessing Piaget's four stages of development using ITS poses challenges due to cognitive development's complexity and multifaceted nature. Piaget's theory emphasizes qualitative changes in thinking patterns and structures as individuals progress through different stages [15]. While ITS can provide valuable insights into learners' performance and progress in specific skills or knowledge domains, assessing the nuanced aspects of cognitive development outlined in Piaget's theory may require additional methods and measures. Therefore, integrating ITS with alternative assessment approaches, such as structured observations, can provide a more comprehensive understanding to the teachers of learners' cognitive development and their progression through Piaget's stages.

2.2. Numeracy Item Analysis

Item analysis plays a crucial role in early-age education for numeracy tasks as it provides valuable insights into the effectiveness of instructional materials and helps identify areas where students may be struggling. By examining individual item performance, educators can better understand students' strengths and weaknesses, allowing for targeted interventions and instructional adaptations. Additionally, item analysis facilitates the identification of problematic items that may be ambiguous or misaligned with intended learning outcomes, improving assessment validity and reliability [16]. Accordingly, those concerns are prominent for ITS as they enable implementing the outer loop by revealing insights on students' strengths and weaknesses, which are used to inform the selection of subsequent learning activities [7] and in the inner loop, once we have categorized the items based on their complexity, difficulty, and or specific numeracy domains, the teacher will be able to adjust their pedagogical approach to the appropriate level of cognitive development of the students.

3. ITS Unplugged Workflow

Assuming that access to technological devices is a barrier that disadvantages underserved students, and we focus on the solution to help the teacher work in the classroom, the ITS unplugged workflow solution follows a structured flow that integrates it into the existing school curriculum-based lesson plan. Figure 1 shows this flow and the user interfaces of our ITS solution.

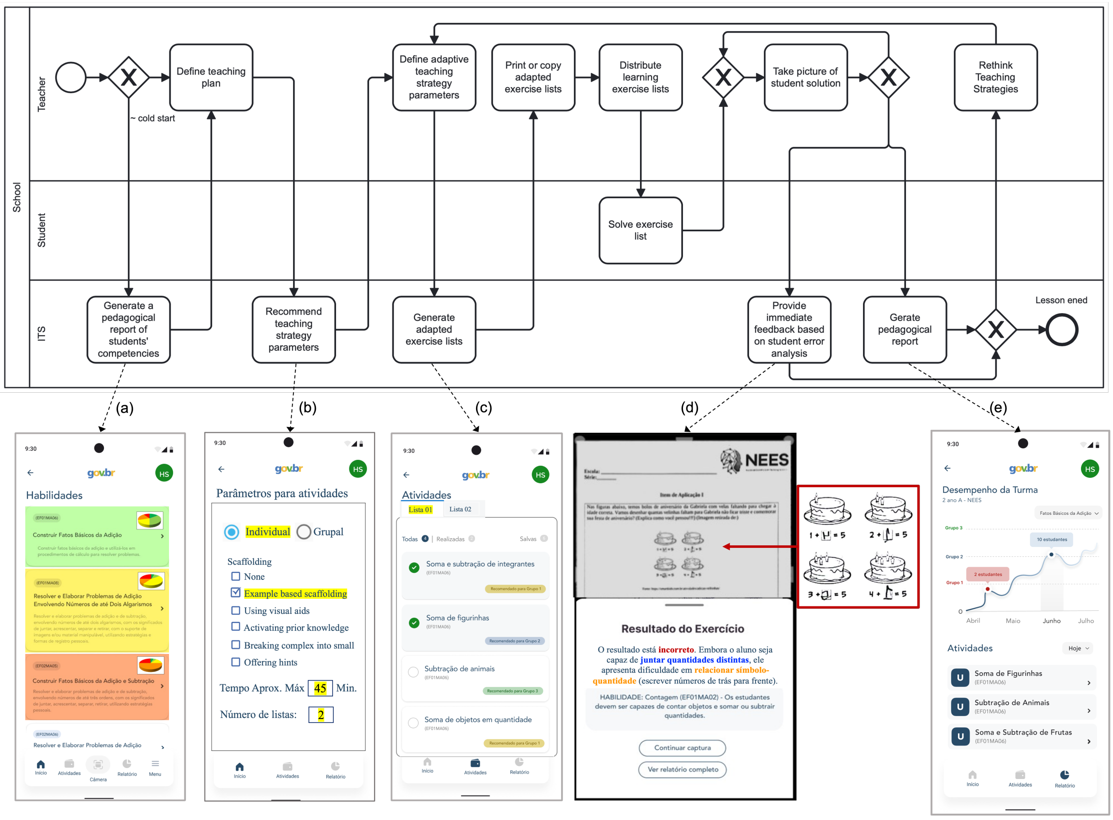

Figure 1: Workflow of a pedagogical approach proposed that integrates curriculum-based lesson plans, computer vision, and natural language processing for numeracy instruction using the ITS unplugged as a pedagogical resource for teachers.

In the initial stage, when teachers develop a lesson plan based on specific skills and learning outcomes in the school curriculum, the ITS unplugged solution helps (a) *generate a pedagogical report that displays students' learning outcomes*. This report assists in defining a teaching plan by showing students' current skill levels in the class. The user interface example uses a color scheme (green, yellow, and red) to indicate adequate, medium, and poor skill levels. Additionally, a graph in the top left corner of each skill visually represents the distribution of skill levels among the students in the classroom.

After defining the teaching plan, our ITS unplugged solution can (b) *recommend teaching strategy parameters* that will be used for solving numeracy problems. In the example of our user interface, these parameters include the modality of solving problems (individual or group), the instructional scaffolding techniques to be utilized in the problems (none, example-based scaffolding, visual aids, activating prior knowledge, breaking complex problems into small problems, and offering hints), the maximum time for solving the lists in the classroom, and the number of lists the ITS will generate. Based on these characteristics, our ITS unplugged solution will (c) *generate adapted lists* for the students to do in the classroom. In contrast to traditional ITS, which generates individualized lists for each student, our ITS unplugged solution provides lists to the teachers for printing and distribution to students respecting their cognitive development stage [15]. Due to logistical constraints, creating a list for each student in the class may be challenging. Instead, a smaller number of lists, typically two or three, would be generated for all the students in the class (and this number is defined in the teaching strategy parameters).

The teacher photographs student solutions after each student solves one problem or completes the activity list. The taken images are input into the ITS unplugged solution, where computer vision techniques are used to recognize and extract relevant handwritten responses. Natural language processing can be used for this analysis, and the responses are examined to evaluate students' understanding, identify common misconceptions, and assess the skill level of mastery for certain numeracy concepts. In this regard, for this analysis, we will use numeracy item analysis to determine individual student performance, identify areas of difficulty, and determine the efficiency of instructional materials and tactics.

As a result of this process, our solution can (d) *provide immediate feedback based on student error analysis* or (e) *generate a pedagogical report*. The immediate feedback offers the teacher insights, identifying strengths and problems and indicating which precise areas require instructional focus. The user interface for this immediate feedback is shown in Figure 1 (d), where it is possible to see that our proposed ITS solution indicates that the students' solution is incorrect, that the students can join distinct quantities, and that there is difficulty relating symbol-quantity, which is a structural problem such as writing number backward. The pedagogical report presents the evolution of the student's class's skill levels based on the evidence and feedback provided by the ITS unplugged solution.

Based on reports and immediate feedback, adaptive teaching can play its role, changing the modality of solving problems (individual or group), the instructional scaffolding techniques, the maximum time for solving the lists in the classroom, and the number of lists that will be generated (see Figure 1 (b)). Following this flow, it enables teachers to leverage the ITS unplugged solution to capture, analyze, and utilize student responses to enhance their teaching approaches. The iterative nature of the workflow, facilitated by the pedagogical report, supports adaptive teaching, allowing teachers to address students' individual needs and promote effective numeracy education.

4. Final Considerations

This paper introduces a pioneering pedagogical workflow that integrates the ITS unplugged solution into a school curriculum-based lesson plan to bridge the digital divide and enhance numeracy education for underserved populations. By harnessing computer vision and natural language processing techniques, the ITS unplugged enables the capture and analysis of students' responses to numeracy tasks through photographs. The systematic workflow outlined in this paper facilitates the generation of a pedagogical report, which provides valuable insights derived from numeracy item analysis. This report is a valuable tool for teachers, offering a deeper understanding of students' performance, highlighting areas of difficulty, and providing recommendations to support adaptive teaching strategies. Incorporating the ITS unplugged solution within the curriculum might empower educators to make informed decisions and adapt their instructional approaches, ultimately fostering effective and tailored numeracy instruction for underserved populations.

Furthermore, as future work, it is recommended to conduct a pilot study involving teachers who instruct children within the target age range for numeracy analysis. This step would allow for the collection of valuable feedback on the applicability and effectiveness of the proposed framework in educational practice. Involving teachers in this pilot implementation process can provide additional insights into the specific needs of children regarding numeracy instruction and identify potential improvements or adjustments to be made to the framework. It would also be interesting to explore the extension of the use of ITS unplugged in other areas of the curriculum, thereby expanding its potential educational impact. These future investigations are crucial for continuously refining the proposed approach and maximizing its benefits for numeracy education in underserved populations.

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