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Fostering Strategic Choice-Making Through Motivational Pedagogical Agents in an Adaptive Learning System

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Abstract: Pedagogical agents in adaptive learning systems can enhance learning outcomes and support self-regulated learning processes, but their role in fostering strategic choice making remains underexplored. To fill the gap, this project designs an interactive algebra learning system with motivational pedagogical agents to foster learning and choice-making behaviors. To test its effectiveness, we conducted a classroom experiment with 49 students with findings that shed light to the future design of adaptive learning environments.

Introduction

Adaptive learning systems offer promising implications to enhance learning outcomes and foster self-regulated learning (SRL) processes, often by embedding adaptive prompts delivered by pedagogical agents (PAs) in real-time to foster engagement, scaffold complex tasks, and offer personalized feedback (Mumm & Mutlu, 2011; Zeitlhofer et al., 2023). For instance, Betty's Brain leverages the use of PAs to provide strategic hints (viz., hints that support debugging and assessment of causal models) that guide learners to monitor performance, reflect on actions, and make informed decisions (Munshi et al., 2023). Despite the integration of PAs into adaptive learning systems, a critical gap remains in understanding how PAs influence students' choice-making behaviors (Nagashima et al., 2022; 2023). Often, the choice-making process was examined through aggregated metrics such as task completion rates rather than granular process data like problem-solving pathways. This limitation prevents a nuanced understanding of how learners dynamically interact with PAs, highlighting the need for research that captures the fine-grained mechanisms underlying choice-making within adaptive learning environments.

To fill this gap, the central question we address is: *How do PAs with motivational prompts influence students' conceptual understanding and strategic choice-making in an adaptive learning system, and how are these effects shaped by prior knowledge over time?*

Learning Environment

Our adaptive learning software, AlgeSPACE (Algebra Scaffolding with Pedagogical Agents and Concrete Examples), incorporates pedagogical agents to guide students in step-by-step, "learning-by-doing" tasks. During problem-solving, the PAs will not only provide instructional scaffolds but also motivational prompts that encourage students to engage in various optional tasks such as self-explaining their previous choices, comparing their selected solution method with a fictional peer's method, or going through worked examples at the beginning. These motivational prompts are designed based on Expectancy-Value Theory (Eccles & Wigfield, 2002) which aim to enhance intrinsic motivation by emphasizing task relevancy and utility. For instance, in one type of exercise, students would be presented with several choice-making opportunities, to which they would select "Yes" or "No." As illustrated in Figure 1, after students successfully selected the most efficient solution method, they received the following message, which not only provides performance-based feedback but also prompts them to engage in a self-explanation task by stating the value of self-explanation: "That's right! Would you like to explain why the substitution method is particularly suitable for the given linear systems of equations? Explaining helps you to retain information for longer. You memorize better what you understand and what you still need to learn." Note that a central design principle in our choice architecture for such optional tasks is to allow students to proceed to the next step regardless of the choice they make. That is, even if students do not want to self-explain, they can still proceed to the next step, without receiving any positive/negative messages that signals if their choice was good or bad. This principle aligns with Chin et al (2019) which prioritizes learner autonomy over compliance. The tool is available both in English and German languages, and we used the German version in the study.

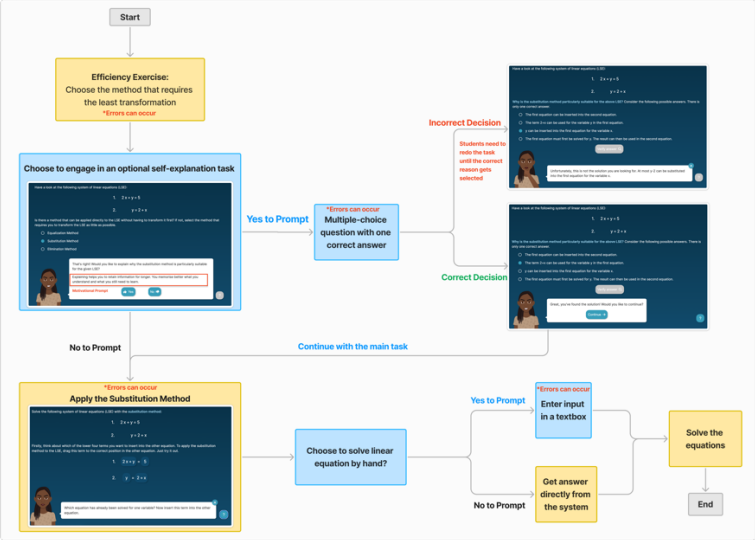
The Classroom Study

We conducted a study with 49 German high-school students from grade 9 and 10 to examine the effects of pedagogical agents with motivational prompts on their conceptual understanding of linear systems of equations and choice-making behaviors. The study included two conditions: one where students interacted with a version of the system featuring PAs with motivational prompts (Agent condition) and another version without motivational agents (Non-Agent condition). Note that both conditions were given the same choice-making

opportunities and problems. They differed only in terms of whether the system provides motivational messages when suggesting engaging in an optional task, accompanied by pedagogical agents. The study was conducted during regular school hours in a university classroom setting, which lasted for approximately one hour. The procedure consisted of five main phases, starting with a 10-minute paper-based pretest on linear equations. Then, students received an interactive tutorial introducing the system, followed by a 25-minute learning session using the system. Upon completing the learning session, students took a paper-based posttest for 10 minutes, which mirrored the pretest with isomorphic exercises. Finally, students filled out a brief questionnaire assessing perceived utility value of the tool and motivational prompts. All students were provided with a tablet for the study.

Figure 1

Steps illustration for an exercise with optional tasks.



Results and Implications

Conceptual understanding was assessed through pre- and posttests, each containing three exercises measuring method selection accuracy, mathematical justification, and procedural (max 18 points per test). Pretest scores were used to classify students into high- (n = 24) or low-prior-knowledge (n = 25) groups via median split. Choice-making behavior was first measured by quantifying choice-making frequency, the proportion of "Yes" responses to total choice-making opportunities (range: 0–1). Lag sequential analysis (LSA) and process mining (PM) techniques were used to identify micro-level choice-making behaviors and macro-level regulatory trajectories across different prior knowledge groups.

For learning gains, results from two-way ANOVAs showed a significant main effect of prior knowledge, $F(1, 45) = 14.98$, $p < .001$). The main effect of condition approached significance ($F(1, 45) = 3.62$, $p = .064$), indicating that students in the Agent condition showed a trend towards higher gains. However, there was no significant interaction effect between Prior Knowledge and Condition ($F(1, 45) = 0.11$, $p = .738$). Post-hoc analyses indicated that the Agent LPK group achieved significantly higher learning gains compared to the Non-Agent HPK group ($p = .002$). For choice-making frequency, although overall choice-making frequencies did not significantly differ between conditions, we observed nuanced differences in specific choice-making scenarios. Specifically, LSA and PM analyses revealed that HPK students exhibited confidence-driven behaviors, bypassing preparatory tasks, and quickly jumping into challenging tasks after successes, though sometimes at the cost of repeated failures. In contrast, LPK students took a cautious and deliberate approach, which relied on foundational tasks such as going through worked examples to build confidence over time. This fine-grained analysis reveals diverse pathways that learners take as they engage with learning tasks dynamically within adaptive systems (Saint et al., 2020; He et al., 2024).

Our research contributes to the ongoing discourse on designing effective adaptive learning environments, taking special account for fostering strategic choice making while promoting conceptual understanding. Future work should continue exploring pedagogical agent scaffolding mechanisms to enhance the choice architecture, extending our findings across diverse STEM domains, and leveraging multimodal analytical methods to ensure adaptive technologies effectively support all learners in executing strategic choice-making behaviors, regardless of their starting point.

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