Students' Self-Regulated Use of Diagrams in a Choice-based Intelligent Tutoring System

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Abstract: Learners' choices as to whether and how to use visual representations during learning are an important yet understudied aspect of self-regulated learning. To gain insight, we developed a *choice-based* intelligent tutor in which students can choose whether and when to use diagrams to aid their problem solving in algebra. In an exploratory classroom study with 26 students, we investigated how learners choose diagrams and how their choice behaviors relate to learning outcomes. Students who *proactively* chose to use diagrams achieved higher learning outcomes than those who *reactively* used diagrams when they made incorrect attempts. This study contributes to understanding of self-regulated use of visual representations during problem solving.

Introduction

In many modern societies, people have access to large amounts of information and resources. Learners therefore need to strategically choose to use available resources so that they can handle learning tasks effectively and efficiently (Schwartz & Arena, 2013). One important class of learner choices involves the use of visual representations. Visual representations can be used as instructional scaffolds that help learners' sense-making processes during learning and problem-solving (Ainsworth, 2006; Rau, 2017). From a cognitive perspective, engaging with visual representations during problem solving can help learners by reducing cognitive effort and making relevant information salient (Ainsworth, 2006). However, to reap these benefits, learners must use visual representations strategically (diSessa, 2004). The strategic, self-directed use of visual representations is an important, though understudied, form of self-regulated learning. To use visual representations strategically, learners need to regulate their behavior (i.e., choose when and how to use visual representations) based on self-monitoring of their own skills and knowledge (Pintrich, 1999).

Despite the importance of understanding learner choices with visual representations, past research has rarely allowed for or specifically measured learner choices in using visual representations during problem solving. Prior work has largely focused on student learning when students are *given* visual representations (e.g., Rau et al., 2015). A few studies have investigated learners' spontaneous use of visual representations (e.g., students constructing diagrams on their own) in problem solving and these studies have shown that students generally tend not to choose to use visual representations when it is optional to do so (Uesaka et al., 2007, 2010). Although prompts to engage with visual representations (e.g., drawing) have been shown effective in encouraging students to use visuals (Wu et al., 2020), past studies do not give deep insights into *how* students make choices in problem solving and how their choices might be related to learning outcomes and performance. A deeper understanding of students' choice-making processes and how they relate to learning could contribute to the understanding of self-regulated learning with visual representations (diSessa, 2004; Zimmerman & Campillo, 2003).

Choice-based Intelligent Tutor with Visual Representations

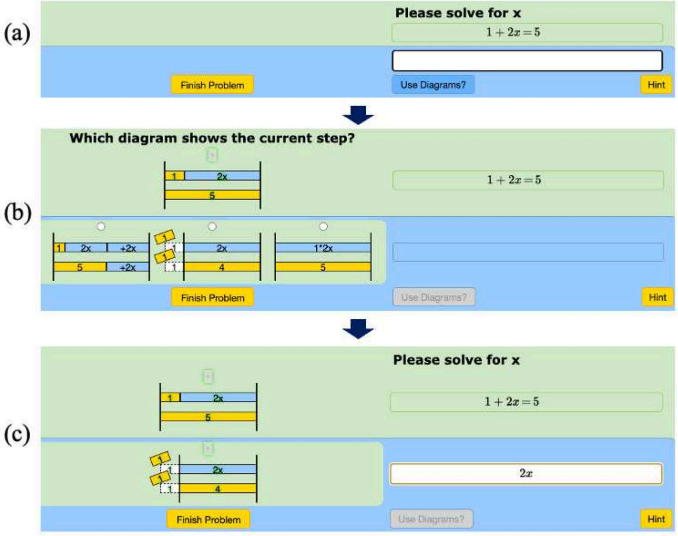
To investigate students' choices in using visual representations, we redesigned an existing Intelligent Tutoring System (ITS) for algebra problem solving (Long & Aleven, 2014; Nagashima et al., 2021) to develop a *Choice-based Diagram Tutor* (Figure 1). In this *choice-based* tutoring system, students can choose whether and when to engage with a visual scaffolding strategy called "anticipatory diagrammatic self-explanation" with tape diagrams, a representation that is increasingly being used in algebra instruction worldwide (Murata, 2008). Anticipatory diagrammatic self-explanation is a metacognitive scaffold in which learners *self-explain* ensuing problem-solving steps by selecting a diagrammatic representation of a next step (Nagashima et al., 2021).

Anticipatory diagrammatic self-explanation presents a fruitful context for examining students' self-regulated choices with visual representations. It is an effective metacognitive strategy that learners might not naturally choose to engage with, a critical prerequisite when designing a "choice-based" learning environment (Chin et al., 2019). In the tutor, students may be inclined to avoid using diagrams because doing so would require additional problem-solving steps. Also, tape diagrams are a new representation that students may find unfamiliar (Murata, 2008). However, anticipatory diagrammatic self-explanation has been shown to be beneficial for student learning and performance (Nagashima et al., 2021). Therefore, we investigated students' *spontaneous use of diagrams* (i.e., whether students spontaneously use diagrams when such use is optional; Uesaka et al., 2010).

Additionally, we distinguish the following choice behaviors involving spontaneous diagram use to get insights into students' self-regulated use of diagrams: 1) *proactive diagram use:* using diagrams *before* attempting to solve the corresponding symbolic step, and 2) *reactive diagram use*: using diagrams *after* making one or more incorrect attempts on the symbolic step. These choice categories are informed by the literature on help-seeking in ITSs (Aleven & Koedinger, 2001) and by Zimmerman and Campillo's (2003) cyclical model of self-regulation. Zimmerman and Campillo's (2003) model captures phases of self-regulated behaviors in which learners evaluate the difficulty of the target task ("forethought" phase), self-monitor learning strategies ("performance" phase), and evaluate and reflect on the use of the strategy ("self-reflection" phase). Under this model, in the Choice-based Diagram Tutor, students may choose to use diagrams by assessing the difficulty of the given equation, self-monitor how they perform by using diagrams, and adjust their use of the strategy through self-reflection. Therefore, we expected that proactive diagram use would represent self-regulated, *well-planned* use of diagrams, whereas reactive diagram use would represent *unplanned* diagram use.

The Choice-based Diagram Tutor collects learning process data (e.g., choice behaviors and problem-solving performance measures), enabling us to study students' learning processes, which have not been explored in studies on spontaneous diagram use (e.g., Uesaka et al., 2010). The present study asks: RQ1) *When given a choice, how will students engage with anticipatory diagrammatic self-explanation?* RQ2) *Are students' choice behaviors related to their learning outcomes, performance, and their perceptions regarding diagram use?*

Figure 1
(a) Students start with an interface showing a symbolic algebra problem. They can solve the equation symbolically or choose to use diagrams ("Use Diagrams?" button). (b) Students who choose to use diagrams will select a correct diagram that represents a good next step. (c) After selecting a correct diagram option, students will type in the step in mathematical symbols.



(a)
Please solve for x
$1+2x=5$

(b)
Which diagram shows the current step?
$1+2x=5$

(c)
Please solve for x
$1+2x=5$
$2x$

Method

We conducted a pretest-intervention-posttest study in two classrooms in a middle school in the U.S. Thirty 6th graders participated. The participating teachers noted that some students might have previously seen tape diagrams in learning materials, but the instruction had never focused specifically on tape diagrams.

We developed a web-based assessment consisting of seven items that measure conceptual understanding of algebra and four procedural knowledge items that asked students to solve symbolic equations. Of these 11 items, three conceptual and two procedural items included tape diagrams. For these problems, tape diagrams were presented either alongside a symbolic equation so that students could refer to them or integrated into the main task (such that students needed to understand the representation to reach the correct answer). Two assessment versions were created and assigned as pretest and posttest in a counter-balanced way. Following the posttest, students answered five survey questions about their perceptions of tape diagrams (e.g., “Do you think that diagrams helped you solve problems?”) and their confidence in solving equations (based on a questionnaire in Uesaka et al., 2007). All students were given the choice-based diagram tutor, which included 22 problems of four different problem types (called “levels” in the tutor): Level 1) $x + a = b$, Level 2) $ax + b = c$, Level 3) $ax = bx + c$, and Level 4) $ax + b = cx + d$, assigned in this order. According to the teachers, students had seen Level 1 problems but had never solved equations in a formal way (by subtracting “a” from both sides of “$x + a = b$”).

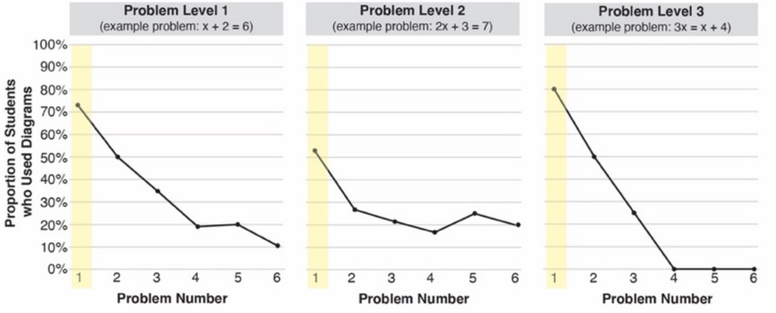
Researchers joined the classrooms remotely to conduct the study. On the first day, students worked on the 10-minute pretest. On the second day, one of the teachers gave a brief lecture on how tape diagrams visualize equations to all students at the beginning of the session. Students then used the tutor for about 25 minutes. Students then completed the posttest and the survey about perceptions of tape diagrams and their math skills.

Results

Four students were absent on the second day of the study; we analyzed data from the remaining 26 students. To answer RQ1, we calculated the frequency of diagram use. On average, students solved 9.12 problems (*SD* = 5.14) and chose to use diagrams 3.15 times overall (*SD* = 2.88). Students *proactively* used diagrams in 72% of cases (*Mean* = 2.27, *SD* = 2.38) and *reactively* used diagrams in 28% of the cases (*Mean* = 0.88, *SD* = 1.21). Students tended to use diagrams on the first problem in each problem level, and diagram use declined as students practiced the same problem type multiple times (Figure 2). The trend was not observed for Level 4 problems because very few participants advanced so far (therefore not included in Figure 2).

Figure 2

Proportion of students who spontaneously used diagrams at least once for each problem.



To examine RQ2, we tested whether self-regulated behaviors predicted learning and performance. We constructed separate linear regression models with the following dependent variables: posttest score, posttest score for problems without tape diagrams, average time spent per symbolic step, average number of hints used per symbolic step, and average number of incorrect attempts for the symbolic steps. We included each of the spontaneous, proactive, and reactive diagram use frequencies in each model as independent variables. Overall pretest score was included to control for students’ initial knowledge level. Spontaneous diagram use predicted higher overall posttest scores; however, this relation did not reach statistical significance ($\beta = 1.47$, $p = .07$). Spontaneous diagram use did not predict any other dependent variables. Proactive diagram use, however, predicted higher overall posttest scores ($\beta = 2.01$, $p < .01$) and higher posttest scores on items without tape diagrams ($\beta = 1.03$, $p = .04$). Reactive diagram use, on the other hand, was associated with lower overall posttest scores ($\beta = -4.75$, $p = .03$) and lower posttest scores on items without tape diagrams ($\beta = -3.39$, $p = .01$). Reactive diagram use also predicted greater use of hints ($\beta = 5.21$, $p < .01$). Prior knowledge, perceptions of diagrams, and confidence in solving equations were not associated with spontaneous, proactive, or reactive diagram use.

Discussion

Although students’ use of diagrams was generally low, students’ *proactive* diagram use predicted higher learning outcomes. This association was also observed on test items that did not include tape diagrams, suggesting near transfer of learning. However, as we cannot establish any causal relationships from the results, it is possible that certain characteristics that we did not control for led both to more proactive diagram use and better learning. For example, proactive diagram use might be indicative of superior monitoring ability or a propensity to monitor one's comprehension more frequently, which might lead to other behaviors that might contribute to better learning.

The current work contributes understanding of self-regulated learning with visual representations. Specifically, it provides evidence that effective use of visual representations involves more than simply using the visual representations spontaneously; rather, proactive use, which we consider as a form of self-regulated diagram use that involves assessment of task difficulty and planning of whether or not to use diagrams, leads to better learning. In a related, pilot study with eight middle-school students who thought aloud as they used the tutor, we found that students who tended to proactively use diagrams thought deeply about the given problem before attempting to solve it and correctly understood diagrams. On the other hand, those with frequent reactive diagram use did not seem to understand the diagrams, and therefore seemed to process diagrams in a shallow way (e.g., selecting diagrams that *look* right). We acknowledge though that different interpretations of these patterns of diagram use may be possible.

Learners can use visual representations in a range of ways. Our data suggest that proactive use of visual representations is beneficial for students' performance. Future research could explore ways to motivate students to use visual representations proactively, help them make self-regulated decisions as to when to spontaneously *fade* visual scaffolding, and experimentally test whether such strategic diagram use might be facilitated.

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