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When Less is More: Students' Use of Diagrams and their Perception of Diagram Use in an AI Tutor for Algebra Learning

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Abstract

It is critical to understand how students' monitoring activities are related to their actions during learning. In particular, studies have not fully explored how students' spontaneous use of visual representations relate to their perception of its usefulness and their learning outcomes, especially in interactive learning environments. This study, using a math intelligent tutoring system, examines the relations between students' perceptions of the usefulness of using diagrammatic scaffolding and their actual patterns of spontaneous diagram use in for secondary-school algebra. Results show that students who evaluated diagrams as useful used diagrams more frequently but showed less learning gains, compared to those who evaluated diagrams as not useful and did not use diagrams frequently. We discuss implications of this finding by connecting with prior work that focuses on drawing as diagram use. This study shows the importance of understanding how spontaneous use of diagrams might or might not help student learning.

Keywords: intelligent tutoring systems, diagram use, visual representations, perception, choice behaviors

Introduction

One important metacognitive activity during human learning is for learners to monitor and regulate the use of certain strategies in the learning environment (Azevedo et al., 2010; Roll et al., 2011). For instance, a student who works on problem-solving tasks may monitor how well they are solving problems, and when they recognize the need for help, they may ask for help in an appropriate manner (e.g., adaptive hints in learning technology, Aleven et al., 2006). Students may also reflect on their learning progress during learning, supported by, for instance, a learner-facing learning analytics dashboard (Bodily & Verbert, 2017) or reflection prompts (Nagashima et al., 2023). Carlson and Bloom (2005) state that successful problem solving involves not only using cognitive resources, knowledge, and skills but it also involves metacognitive processes where learners regulate their problem-solving process. Accurately and strategically monitoring how learners are using certain strategies and how the use of such strategies help (or does not help) their own learning can lead to effective self-regulated learning (Zimmerman & Campillo, 2003).

Strategy use and its relation to learning has been investigated particularly in computer-based learning

environments on a variety of metacognitive behaviors, including the use of help-seeking strategies (Aleven et al. 2006; Roll et al., 2011), use of optional resources in a hyper-media environment (Azevedo et al., 2022), and use of textual and graphical representations (Schwonke et al. 2013). These interactive learning environments withhold prescriptive scaffolding (based on, e.g., the system's understanding of learner's knowledge state) but rather allow learners to own the control on making choices and measure students' behaviors in such an environment.

One such metacognitive strategy involves the use of visual representations during learning. Visual representations, such as diagrams, illustrations, and drawings, are often used as instructional scaffolding, aimed at supporting students' problem solving and learning (Ainsworth & Scheiter, 2021). Visual representations help learners understand the problem as they approach problem solving. For instance, diagrams may highlight important features in the problem using visual cues, thereby making it cognitively easier for students to understand what to focus on during the task (Barbieri et al., 2019; Nagashima et al. 2020).

Many prior studies in this domain on the use of visual scaffolding focuses on *learning with visual representations* (Booth & Koedinger, 2012; Chu et al., 2017; Rau et al., 2015); learners are presented and/or asked to use visual representations where research questions tend to focus on whether such prescribed visual scaffolding helps learners (Zahner & Corter, 2010). These studies typically do not allow learners to make informed decisions on whether or not to use the visual scaffolding.

On the other hand, *learning to strategically use visual representations* in problem solving, despite its critical role in metacognitively supporting student learning, has gained little attention in the literature. Few studies have investigated learners' spontaneous diagram use during problem solving when it is optional to do so (e.g., Corter & Zahner, 2007; Uesaka & Malano, 2012; Zahner & Corter, 2010). For instance, Uesaka et al. (2007) found that students who perceive that diagrams are useful are more likely to spontaneously draw diagrams during problem solving. Wu et al. (2020) evaluated the use of prompts to encourage students to draw diagrams in an electrical engineering class. They found that students who were prompted to draw diagrams

self-reported that they had drawn diagrams more frequently and found it valuable as a learning strategy, compared to students who did not receive drawing prompts.

However, these past studies have mostly focused on student-generated visual representations in the form of drawing, but not on other types of visual representations. Student-generated drawing is considered a “constructive” activity according to Chi’s ICAP framework (Chi & Wylie, 2014), which requires learners to engage with generative behaviors to make sense of the task (Fiorella & Zhang, 2018). Although such a constructive activity is beneficial for learning, it is also worth considering other forms of interacting with visual representations, such as the spontaneous use of interactive diagrams provided within a computer-based learning environment (which is more scaffolded than student-generated drawings). Given the increased use of interactive learning technologies for both research and practice (e.g., Cognitive Tutors, Koedinger & Alevan, 2016; Ritters et al., 2007), it is important to test how students would spontaneously use and perceive the use of visual representations in such a learning environment.

The Diagram Choice Tutor

To measure students’ use of visual representations and monitoring/perceptions during learning in an interactive technology, we developed the *Diagram Choice Tutor*, math intelligent tutoring software where learners can choose to use or not to use visual scaffolding for every step of solving equation problems (Figures 1-3). In the Diagram Choice Tutor, when learners choose to use visual scaffolding, they will then be prompted to select one “tape diagram” (Murata, 2008) option that represents a correct next step of equation solving among three options given. After selecting the diagram, they will use that as a visual scaffold to work on the step in the standard format using mathematical symbols. This “anticipative” way of using visual scaffolding (i.e., selecting diagrams that depict future problem-solving steps) has been shown effective in supporting student learning (Nagashima, Bartel, et al., 2021).

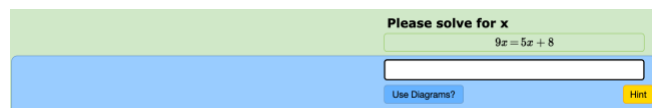


Figure 1: In the tutor, students solve equations, with or without the help of interactive diagrammatic scaffold.

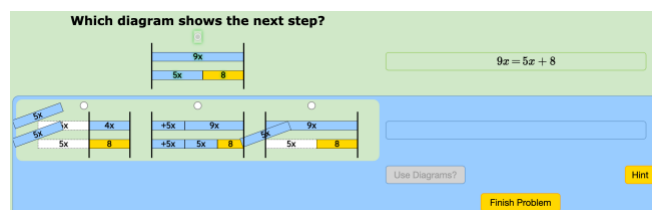


Figure 2: By clicking on the “Use Diagrams?” button, students can request a diagram step. Once they click on it,

they will choose a correct visual representation for what to do next, among the three options that are automatically generated by the system.

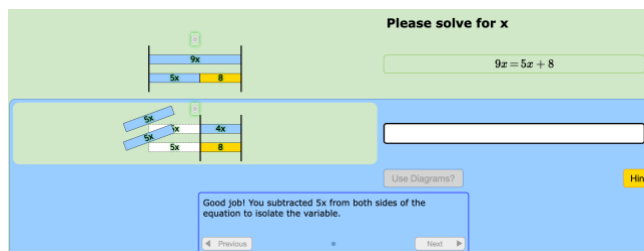


Figure 3: Once they choose the correct representation, students will go back to the symbolic equation solving (they can use the diagrams as a reference to fill in the symbolic input area on the right).

To support students’ metacognitive learning processes, the tutor also embeds three additional metacognitive prompts (Figures 4-6). These additional metacognitive prompts include: 1) an interactive tutorial that shows how diagrams could be useful for solving equations (Figure 4), 2) adaptive recommendations that pop up when the system detects that the learner might be having trouble solving the problem (e.g., when a learner makes three incorrect attempts in a row) (Figure 5), and 3) a student-facing learning analytics dashboard that shows how well the learner is solving when they chose to use diagrams and when they did not choose to use diagrams (Figure 6). Specifically, the dashboard displays a bar graph showing their success/correctness rate of problem solving, divided into when the student chose to use diagrams and when they did not, for the past four problems in the tutor (grouped as “levels”). In other words, it promotes students’ active comparison of their problem-solving performance for each of the two choice-making scenarios (with diagrams or without diagrams) so that students can reflect on whether their choices were beneficial or not.

The dashboard also has an explicit self-reflection prompt asking the learner to rate, using a “smiley scale,” how much usefulness they perceive in using diagrams for solving equations (Figure 6). The smiley scale is a 5-likert scale ranging from “Not at all” to “Extremely,” introduced to help school students quickly react to the prompt (instead of giving a text-based scale). After responding to the smiley scale, the learner will be asked to provide reasoning for their rating in an open-ended text input format. The dashboard was placed after each problem unit in the tutor (we provide a more description of how the problems were structured in the Materials section). These three prompts were iteratively co-designed with eight middle-school students in the US in the early phase of tutor development.

The Diagram Choice Tutor offers an appropriate learning and assessment environment to explore students’ behaviors of using visual scaffolding when it is optional and how their monitoring relates to their behaviors of diagram use. The tutor logs step-by-step interactions between the student and

the tutor for analysis. For the current study, we extracted the frequency of diagram use (i.e., how many times students chose to use diagrams in each problem) and students' perception of the usefulness of using diagrams (i.e., smiley scale).

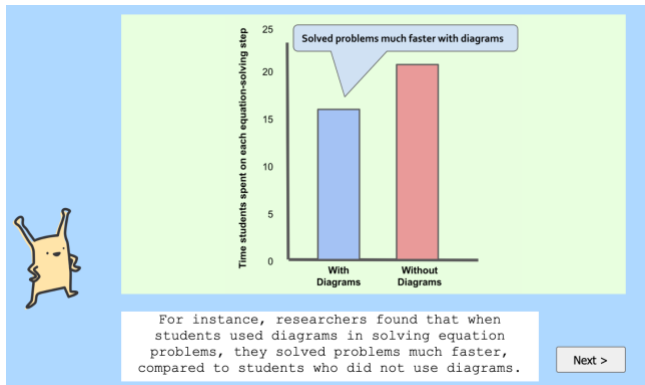


Figure 4: An interactive tutorial that informs students how the use of diagrams might benefit their problem solving.

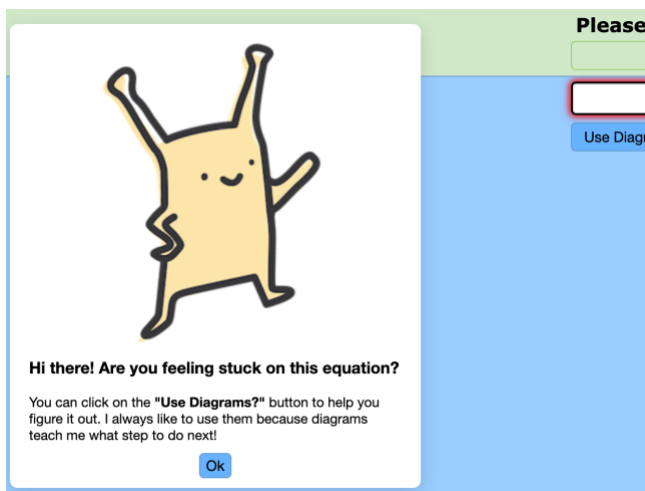


Figure 5: A recommendation window shows up when the system detects students' struggles (indicated by three consecutive mistakes and long pause). The recommendation suggests that the student consider using diagrams.

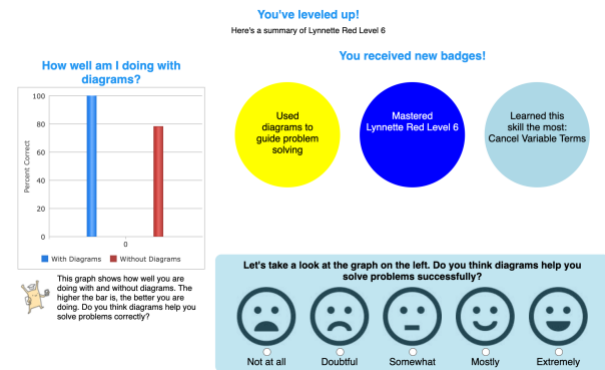


Figure 6: A dashboard that shows (in a bar graph) the student's correctness rate of the problem solving when they chose to request/use diagrams (in blue) and when they did not do so (in red). On the right, it shows several accomplishment badges (based on the student's performance) and an explicit self-reflection prompt asking students to rate how useful they perceive in using diagrams.

The Present Study

We address the following research question in this paper: *How are students' use of diagrams, perceptions of using diagrams, and learning related to each other?* Past research documents the general benefits of using visual scaffolding for learning in math (e.g., Booth & Koedinger, 2012; Chu et al., 2023; Nagashima et al., 2020). In the context of the Diagram Choice Tutor, we hypothesized that students who use diagrams more frequently would perform well in the tutor (due to the scaffolding provided), learn well, and perceive diagrams positively.

Method

The data reported here were collected as part of a larger research project in which we conducted a classroom study with 140 secondary-school students on whether the Diagram Choice Tutor would help students choose to use diagrams strategically and gain greater conceptual and procedural learning, compared to the version of the tutor with none of the three metacognitive interventions. As illustrated above, the Diagram Choice Tutor has a student-facing dashboard at the end of each problem level that summarizes their problem-solving performance (in a bar graph) with a self-reflection prompt asking the student to rate how useful they perceived diagrams are (Figure 6). We take temporal data from this prompt to understand students' perceptions of the usefulness of using diagrams while learning.

Participants

The present study analyzes data from 69 participants (out of 140 in a larger research study) in one of the conditions since there is no perception data collected from the other condition (i.e., the other condition did not receive the dashboard). These 69 students include 16 5th graders, 17 6th graders, 31 7th

graders, and 5 8th graders from two schools, across 11 classes.

Materials

The participants practiced equation solving using the Diagram Choice Tutor. Table 1 shows the types of equations students practiced and how they were arranged into different difficulty levels. The dashboard was given at the end of each problem level. The tutorial was assigned before starting to solve equations, and the recommendations were available in all problem levels, triggered when students made certain actions as described above.

Students solved a web-based pretest before using the tutor and an isomorphic version of the test (where specific numbers used for problems were changed) as a posttest after using the tutor. These tests included 16 multiple-choice conceptual knowledge items and five open-ended procedural knowledge items (e.g., “Solve for x : $2x + 3 = 7$ ”). These items were developed based on items used in the literature (e.g., Booth et al. 2013).

Table 1: Types of equation problems assigned in the tutor.

Problem level	Problem type	Number of problems in the level
1	$x + a = b$	4
2	$ax + b = c$	4
3	$ax + b = c$	4
4	$ax = bx + c$	4
5	$ax = bx + c$	4
6	$ax + b = cx + d$	4
7	$ax + b = cx + d$	4
8	$ax + b = c$	4
9	$ax = bx + c$	4
10	$ax + b = cx + d$	4
11	$ax = bx + c$	4
12	$ax + b = cx + d$	4

Procedure

The study was implemented over five consecutive school days in 2022 during students’ regular class schedules. Due to COVID-19 precautions (Nagashima, Yadav, et al., 2021), researchers participated in the sessions remotely via a video conferencing platform. On the first day, students completed an online pretest, followed by a short instructional video demonstrating how to navigate the tutoring system (this video did not address the potential benefits of using diagrams). From the second through the fourth day, students engaged with algebra problems using the Diagram Choice Tutor. On the fifth day, they completed an online posttest. Afterward, all participants were given access to both versions of the tutor, allowing them to explore each condition’s interface without further data logging.

Results

Table 2 shows descriptive data on students’ performance on pretest and posttest. We first conducted repeated-measure ANOVAs to measure learning gains from pretest to posttest. We found that students learned from the intervention, showing increases in conceptual ($F(1, 68) = 4.07, p = .048, \eta^2 = 0.02$) and procedural knowledge ($F(1, 68) = 36.93, p < .001, \eta^2 = 0.09$) after using the Diagram Choice Tutor. Also, on average, students finished 32.64 problems in the tutor ($SD = 13.52$), meaning that, on average, students reached Level 8 (Table 1). As shown in Table 3, on average (i.e., across all problems in the tutor), students chose to request diagrams 0.35 times per equation-solving step ($SD = .32$). This translates to 0.78 times for each problem on average ($SD = .65$) (but note that problems require different numbers of steps, depending on their difficulty). Table 3 also shows students’ perceived usefulness in using diagrams aggregated across all levels (measured using the “smiley scale” on the dashboard). We coded students’ response on the smiley scale as follows: *Not at all* (useful) = 1, *Doubtful* = 2, *Somewhat* = 3, *Mostly* = 4, and *Extremely* (useful) = 5. The results show that students generally expressed a positive attitude towards using diagrams (mean score = 3.35, $SD = 1.38$).

Table 2: Mean pretest and posttest scores (standard deviation).

Pretest		Posttest	
Conceptual knowledge	Procedural knowledge	Conceptual knowledge	Procedural knowledge
9.78	1.74	10.48	2.88
(2.72)	(1.74)	(2.49)	(2.03)

Table 3: Mean frequency of diagram use and perceived usefulness in using diagrams (standard deviation).

Mean frequency of diagram use in the tutor		Perceived usefulness in using diagrams
Per problem solving step	Per problem	
.35 (.32)	.78 (.65)	3.35 (1.38)

We then examined predictive relations among students’ diagram use, their perception of how useful diagrams are, and their learning of conceptual and procedural knowledge. As the homoscedasticity assumption was not met, we used the Huber-White method for conducting linear regressions below. We found that students who evaluated diagrams more positively tended to use diagrams more frequently, $\beta = .66, t(66) = 8.51, p < .001$. Those who considered diagrams useful, however, tended to solve fewer problems in the tutor, $\beta = -.27, t(66) = -2.68, p = .009$ and they scored worse on the pretest, both on conceptual knowledge ($\beta = -.28, t(66) = -2.40, p = .019$) and procedural knowledge ($\beta = -.31, t(66) = -2.63, p = .011$). After controlling for pretest scores, students’ perceived usefulness of using diagrams still significantly

predicts posttest scores in conceptual ($\beta = -.24$, $t(66) = -2.13$, $p = .037$) and procedural knowledge ($\beta = -.16$, $t(66) = -2.26$, $p = .027$) in a negative direction. These results suggest that students with low prior knowledge tended to use diagrams more often, evaluated them as useful, but did not learn much from pretest to posttest on conceptual and procedural understanding of algebra. On the other hand, students with higher prior knowledge tended *not* to use diagrams very often and evaluated diagrams as *not* useful but still showed greater learning from pretest to posttest. Hence, we partially confirm our hypothesis; students who evaluated diagrams more positively tended to use them more often, but learned less conceptual and procedural knowledge.

Discussion

In this study, we investigated students' use of diagrams as visual scaffold during algebra problem solving, their perception of the usefulness of using diagrams, and learning outcomes. Interestingly, contrary to some previous findings suggesting that frequent use of diagrams is associated with better learning in math (Uesaka et al., 2007), our results indicate that students who used diagrams more frequently and viewed them as beneficial tended to show lower learning gains than those who used them less often and rated them less positively.

Why were more frequent use and positive perception associated with less learning gains? One possible explanation is that students were overly reliant on the use of diagrams. Students who frequently requested to have diagrammatic scaffold might have liked the way diagrams guided problem solving (as diagrams show what to do next in the symbolic step, see Figures 1-3), and therefore relied too much on the scaffolding during their learning in the tutor (i.e., over-scaffolding effect). This possible behavior is similar to the "gaming the system" behavior (Baker et al., 2008), where studies show students' non-ideal behavior of excessive use of hint features in intelligent tutors. On the other hand, students who did not use diagrams very frequently might have metacognitively chosen not to do so as they wanted to practice equation solving without relying too much on the scaffold. Even though these students tended to have low prior knowledge (measured via pretest), it is possible that students, by engaging with the three prompts embedded (Figures 4-6), learned when it is most useful to use diagrams, made decisions to regulate their behavior, and achieved higher learning gains.

However, it is important to highlight that the mode of diagram use in the present study is different from what has been the focus of other work (e.g., drawing, in Wu et al., 2020) and this difference has implications for students' cognitive (and metacognitive) processing during learning. Specifically, our Diagram Choice Tutor scaffolds students' diagram use through a simplified task of choosing a correct representation among three contrasting cases given. This is a quicker, less cognitive-load-inducing method of diagrammatic scaffolding, compared to, for example, drawing out a diagram. Drawing would involve more

cognitive efforts in understanding the task and creating their own drawings by perceiving and integrating important features in the task. In such a constructive task (Chi & Wylie, 2014), an over-reliance effect like what we have observed in the present study may not occur.

We acknowledge several limitations of the study. First, the study focused on one specific type of diagram (called tape diagrams) and on a specific interaction embedded in the tutor where students were prompted to select one correct representation among three options. Therefore, findings from this specific context might not generalize across various situations where students would make choices on the use of diagrams. Second, our study has a small sample size of 69. Future studies can test the research question with a larger sample.

Conclusion

An important goal of education is to promote autonomous, self-regulated learners who can make proactive choices to use resources around them during learning. Past work has shown that actively engaging with visual representations when it is optional to do so leads to better learning and perception. We tested how students' use of diagrams, their perception of how useful it is to use diagrams, and their learning relate to each other in the context of intelligent tutoring software with scaffolded diagram use. Our work demonstrated that students' frequent use of diagrams and positive evaluation of using diagrams did not lead to greater learning, suggesting an over-scaffolding effect. Future studies can test different modes of students' diagram/visual use with and without learning technologies.

Acknowledgements

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References

- Ainsworth, S. E., & Scheiter, K. (2021). Learning by drawing visual representations: Potential, purposes, and practical implications. *Current Directions in Psychological Science*, 30(1), 61-67.
- Aleven, V., McLaren, B., Roll, I., & Koedinger, K. (2006). Toward meta-cognitive tutoring: A model of help seeking with a Cognitive Tutor. *International Journal of Artificial Intelligence in Education*, 16(2), 101-128.
- Azevedo, R., Bouchet, F., Duffy, M., Harley, J., Taub, M., Trevors, G., ... & Cerezo, R. (2022). Lessons learned and future directions of metatutor: Leveraging multichannel data to scaffold self-regulated learning with an intelligent tutoring system. *Frontiers in Psychology*, 13, 813632.
- Azevedo, R., Johnson, A., Chauncey, A., & Burkett, C. (2010). Self-regulated learning with MetaTutor: Advancing the science of learning with MetaCognitive

- tools. *New science of learning: Cognition, computers and collaboration in education*, 225-247.
- Barbieri, C. A., Miller-Cotto, D., & Booth, J. L. (2019). Lessening the load of misconceptions: Design-based principles for algebra learning. *Journal of the Learning Sciences*, 28(3), 381-417.
- Bodily, R., & Verbert, K. (2017). Review of research on student-facing learning analytics dashboards and educational recommender systems. *IEEE Transactions on Learning Technologies*, 10(4), 405-418.
- Booth, J. L., & Koedinger, K. R. (2012). Are diagrams always helpful tools? Developmental and individual differences in the effect of presentation format on student problem solving. *British Journal of Educational Psychology*, 82(3), 492-511.
- Carlson, M. P., & Bloom, I. (2005). The cyclic nature of problem solving: An emergent multidimensional problem-solving framework. *Educational Studies in Mathematics*, 58, 45-75.
- Chi, M. T., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist*, 49(4), 219-243.
- Chu, J., Rittle-Johnson, B., & Fyfe, E. R. (2017). Diagrams benefit symbolic problem-solving. *British Journal of Educational Psychology*, 87(2), 273-287.
- Corter, J. E., & Zahner, D. C. (2007). Use of external visual representations in probability problem solving. *Statistics Education Research Journal*, 6(1), 22-50.
- Fiorella, L., & Zhang, Q. (2018). Drawing boundary conditions for learning by drawing. *Educational Psychology Review*, 30, 1115-1137.
- Koedinger, K. R., & Aleven, V. (2016). An interview reflection on "intelligent tutoring goes to school in the big city". *International Journal of Artificial Intelligence in Education*, 26, 13-24.
- Nagashima, T., Bartel, A., Silla, E., Vest, N., Alibali, M. W., & Aleven, V. (2020). Enhancing Conceptual Knowledge in Early Algebra Through Scaffolding Diagrammatic Self-explanation. In *The Interdisciplinarity of the Learning Sciences, 14th International Conference of the Learning Sciences (ICLS) 2020, Volume 1* (pp. 35-42). Nashville, Tennessee: International Society of the Learning Sciences.
- Nagashima, T., Bartel, A. N., Yadav, G., Tseng, S., Vest, N. A., Silla, E. M., Alibali, M. W., & Aleven, V. A. (2021). Using anticipatory diagrammatic self-explanation to support learning and performance in early algebra. In de Vries, E., Hod, Y., & Ahn, J. (Eds.), *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. (pp. 474-481). Bochum, Germany: International Society of the Learning Sciences.
- Nagashima, T., Yadav, G., Aleven, V. (2021). A Framework to Guide Educational Technology Studies in the Evolving Classroom Research Environment. In: De Laet, T., Klemke, R., Alario-Hoyos, C., Hilliger, I., Ortega-Arranz, A. (eds) *Technology-Enhanced Learning for a Free, Safe, and Sustainable World. EC-TEL 2021. Lecture Notes in Computer Science*, vol 12884. Springer, Cham.
- Nagashima, T., Zheng, B., Tseng, S., Ling, E., & Aleven, V. (2023). Promoting students' self-regulated choices in learning with visual representations in intelligent tutoring software. In *Proceedings of the Annual Meeting for the International Society of the Learning Sciences (ISLS2023)*.
- Rau, M. A., Aleven, V., & Rummel, N. (2015). Successful learning with multiple graphical representations and self-explanation prompts. *Journal of Educational Psychology*, 107(1), 30.
- Ritter, S., Anderson, J. R., Koedinger, K. R., & Corbett, A. (2007). Cognitive Tutor: Applied research in mathematics education. *Psychonomic bulletin & review*, 14, 249-255.
- Roll, I., Aleven, V., McLaren, B. M., & Koedinger, K. R. (2011). Improving students' help-seeking skills using metacognitive feedback in an intelligent tutoring system. *Learning and instruction*, 21(2), 267-280..
- Schwonke, R., Ertelt, A., Otieno, C., Renkl, A., Aleven, V., & Salden, R. J. (2013). Metacognitive support promotes an effective use of instructional resources in intelligent tutoring. *Learning and Instruction*, 23, 136-150..
- Uesaka, Y., & Manalo, E. (2012). Task-related factors that influence the spontaneous use of diagrams in math word problems. *Applied Cognitive Psychology*, 26(2), 251-260.
- Uesaka, Y., Manalo, E., & Ichikawa, S. I. (2007). What kinds of perceptions and daily learning behaviors promote students' use of diagrams in mathematics problem solving?. *Learning and Instruction*, 17(3), 322-335.
- Wu, S. P., Van Veen, B., & Rau, M. A. (2020). How drawing prompts can increase cognitive engagement in an active learning engineering course. *Journal of Engineering Education*, 109(4), 723-742.
- Zahner, D., & Corter, J. E. (2010). The process of probability problem solving: Use of external visual representations. *Mathematical Thinking and Learning*, 12(2), 177-204.
- Zimmerman, B. J., & Campillo, M. (2003). Motivating self-regulated problem solvers. *The Psychology of Problem Solving*, 233-262.