REAL: Research in Education Assessment and Learning ISSN: 1947-5497 www.realjournal.org

Research Article in Education Technology

Learning through Diagram-Based Strategies: Effects of Technology-Supported Drawing Environments on Students' Spontaneous Use of Diagrams

Yefeng Lu[1], Qing Wang[2], Emmanuel Manalo[3], Yanyan Zhang[4], Xin Jin[5], Dewei Ye[6],*

[1] School of Teacher Education, Huzhou University, Huzhou, China

[2] School of Educational Science, Taizhou University, Taizhou, China

[3] Graduate School of Education, Kyoto University, Kyoto, Japan

[4] College of Education Science and Technology, Nanjing University of Posts and Telecommunications, Nanjing, China

[5] Jinghengyi Education College, Hangzhou Normal University, Hangzhou, China

[6] Research Center for Learning Science, Southeast University, China

* Corresponding Author: 476485934@qq.com

(Received: 10/20/2025; Accepted: 12/05/2025; Published: 12/19/2025)

DOI: https://doi.org/10.37906/real.2025.1

Abstract: Learning by drawing is increasingly recognized as a powerful learning strategy that facilitates knowledge construction and integration. However, research has rarely examined how technology-supported environments influence students' use of diagram-based learning strategies. This quasi-experimental study involved 72 undergraduate students in a pedagogy course. The experimental group (N=37) used a digital diagramming platform equipped with AI-assisted layout and auto-generation functions, while the control group (N=35) drew diagrams by hand. Both groups received instruction and encouragement in using diagrams as learning strategies. The study found that a technology-supported drawing environment encourages students to use diagrams more spontaneously and enhances the quality of the diagrams they create. However, this environment did not make drawing diagrams feel easier. While it improved the visual appeal of the diagrams, it did not lead to a greater coverage of knowledge points or enhance the accuracy of the meanings conveyed. Pedagogical implications are offered based on the findings.

Keywords: learning by drawing; technology-supported drawing environments; spontaneous diagram production; diagram quality; diagram-based learning strategy

---

1. Introduction

Diagrams are effective tools for visually representing the appearance, structure, or function of information we are dealing with (Luna-Gijón et al., 2025). Their use spans various contexts, including their inclusion in essays, reports, and presentations. Recently, the role of diagrams in learning and instruction has garnered significant attention (Ainsworth et al., 2011; Fiorella & Mayer, 2016; Schmidgall et al., 2019). Many researchers point out that effectively using diagrams can help students organize and reconstruct information, thereby enhancing knowledge retention, understanding, and transfer (Fiorella & Zhang, 2018;

Van Meter & Garner, 2005). Furthermore, diagrams are seen as an efficient means of communication (Ainsworth et al., 2011; Jackel, 2014; Uesaka & Manalo, 2014). Sometimes, a diagram is worth ten thousand words (Larkin & Simon, 1987). Effectively using diagrams enables students to explain and share their ideas clearly and attractively. The problem, however, is that despite the benefits of drawing diagrams as a learning strategy, students seem to lack the spontaneity to incorporate diagrams into various learning tasks (Manalo et al., 2019). Students often perceive drawing strategies as high-risk and associate them primarily with instructional use by teachers (Uesaka et al., 2007). They may worry that engaging in drawing could hinder task efficiency. A more profound constraint arises from the widespread lack of basic diagram skills among students, which is often due to the absence of systematic training in educational practices (Manalo et al., 2019). Many students struggle to create high-quality diagrams, and poor-quality diagrams often fail to support effective learning (Leopold et al., 2013; Schmidgall et al., 2020). Educators need to pay particular attention to these issues, as students' spontaneous use and ability to draw diagrams are essential for realizing the potential of this strategy to enhance learning achievement.

In recent years, with the development of Information and Communication Technology (ICT), some diagramming tools (such as XMind, Microsoft Visio, and xGraph) have greatly facilitated the creation of diagram. These digital tools generally provide basic shapes, online icons, and templates to facilitate diagramming (Chang et al., 2016; Farrokhnia et al., 2019; Gijlers et al., 2013). In particular, the emergence of generative AI (e.g., DALL·E 3) enables the rapid generation of relevant diagrams based on users' prompt (Moundridou et al., 2024). These advancements have created a drawing environment that is entirely different from traditional freehand drawing. Numerous studies have reported the positive impacts of technology-supported diagramming on learning. These impacts include cognitive aspects, such as summarization skills (Hwang et al., 2019) and the ability to organize and connect knowledge (Gurlitt & Renkl, 2008), as well as affective aspects, including attitudes and learning satisfaction (Hsu, 2019). However, these studies only focus on the impact of technology-supported diagramming on learning outcomes, while the influence of technology on the drawing process itself is often overlooked. One key aspect neglected is students' spontaneity in creating diagrams, which is essential for realizing the learning benefits of technology-supported drawing. While technology has made drawing more accessible and can help compensate for students' limited drawing skills, some students may struggle with diagramming tools due to unfamiliarity with ICT, which could hinder their spontaneous use of diagramming strategies. These worries have been highlighted in research on technology-supported learning (Van De Werfhorst et al., 2022; Zhou et al., 2024). Additionally, different types of diagrams have specific functions and cater to different learning objectives. Many drawing tools offer preset templates and elements, allowing users to quickly create diagrams. While this improves efficiency, it may lead students to choose "easily achievable" types of diagrams rather than those that could "best express their ideas." Research in this area is currently limited. Therefore, this study's purpose was to explore whether a diagramming tool can enhance students' spontaneity in using diagrams. Additionally, we will examine how technology-supported drawing environments influence the types and quality of diagrams created by students compared to hand-drawn conditions. These explorations will help clarify the advantages and limitations of technology-supported drawing, providing recommendations for future teaching practices..

2. Literature review

2.1 Benefits and Challenges of Diagram Use by Students

"Learning by drawing" has gained considerable attention in the past few decades. According to Van Meter and Garner (2005), drawing diagrams is a learning strategy where students convert concepts or information into visual representations. This transformation enhances knowledge retention, comprehension, and problem-solving skills. The mechanisms by which drawing diagrams facilitate learning are based on theories such as generative learning theory (Wittrock, 1989) and multimedia learning theory (Mayer & Fiorella, 2021). These theories suggest that encouraging students to translate provided text into drawings supports understanding by promoting cognitive processes of selection, organization, and integration. Additionally, drawing has the advantage of integrating verbal and non-verbal (visual-spatial) information, which helps in constructing coherent mental representations (Shimizu, 2025). Fiorella and Mayer (2016) portrayed drawing as one of the eight effective methods of generative learning. During the drawing process, students actively engage with the material instead of passively receiving information. By using diagrams, learners can organize fragmented information into logical structures, such as mind maps or flowcharts, which facilitates deeper processing of knowledge. A recent meta-analysis found the effect size of drawing diagrams to be 0.69 (Cromley et al., 2020), underscoring its potential as a highly effective learning method.

A persisting problem, however, is the previously mentioned general lack of spontaneity among students in using diagrams while conducting various learning tasks (Manalo et al., 2019). One reason for this is students' perceptions of drawing diagrams. They often see diagrams as a tool that only teachers can use, rather than as part of their own learning strategies. As a result, they rarely use diagrams on their own. Additionally, many students are unaware of the pedagogical benefits that constructing diagrams offer. Only when they personally recognize the value of using diagrams are they likely to incorporate them into their future learning (Manalo & Uesaka, 2014). Another reason is that students lack the necessary skills to create appropriate diagrams. Although teachers frequently use diagrams to assist with problem-solving across various subjects in class, systematic training on diagram construction is rarely provided to students. This lack of training can lead students to invest extra time and cognitive effort in irrelevant processes while drawing (Leopold et al., 2013) or to use diagrams incorrectly, which fails to support their problem-solving process (Heckler, 2010; Stull & Mayer, 2007). Consequently, students often view drawing diagrams as an ineffective strategy and rarely use them.

Based on the findings outlined above, current effective intervention approaches focus on changing students' perceptions of diagrams and providing the necessary training. In a study conducted by Uesaka et al. (2010), they compared the effects of four different intervention conditions: teacher-provided verbal encouragement (VE) combined with practice in drawing diagrams (PD), VE alone, PD alone, and a no-intervention group. The study found that the use of diagrams was most effectively promoted when both VE and PD were provided. They noted that the verbal encouragement from teachers enhanced students' perception of the usefulness of diagrams, helping them realize that using diagrams to solve problems was "worth the effort." Simultaneously, the practice of drawing diagrams equipped students with the necessary skills to create diagrams, making them feel confident that they "could do it." Later, in a study targeting EFL (English as a foreign language) students, Manalo and Uesaka (2016) provided a combined intervention that included advice on diagram use, instruction, and practice. The results indicated that this approach effectively increased students' spontaneous use of diagrams in their written assignments. The effectiveness of this intervention can be explained through broader theoretical models of innovation acceptance and adoption (Davis, 1989; Rogers, 2003; Venkatesh & Davis, 2000). In Davis's (1989) Technology Acceptance Model (TAM), he explained that perceived usefulness and perceived ease of use are critical factors influencing an individual's decision to adopt a new tool or technology. Thus, the intervention by Manalo and Uesaka (2016) can be interpreted as enhancing students perceived usefulness and perceived ease of using diagrams, thereby motivating them to adopt and utilize such a strategy. However, a significant limitation of these studies is that they are confined to hand-drawn conditions, overlooking the influence of diagramming tools. In recent years, the use of ICT in education has expanded significantly, particularly with the widespread adoption of digital devices like tablets in both universities and K-12 schools. This shift has also introduced new tools and opportunities for creating diagrams. Students can create, modify, or refine their diagrams more easily using drawing software, which simplifies processes that would be cumbersome in a traditional pen-and-paper environment (Erdogan, 2009). Therefore, it is essential to incorporate technology as a significant context when discussing students' spontaneity in using diagrams and designing effective interventions. These considerations are of great importance for maximizing the effectiveness of drawing diagrams.

2.2 The Impact of Technology on Diagram Drawing

In the digital age, the way information is presented, transmitted, and communicated in classrooms has changed dramatically (Terzian, 2019). Today, acquiring classroom information is no longer limited to paper-based textbooks or static content written by teachers on blackboards. Instead, students can access and interact with a variety of resources, including graphics, dynamic models, and videos, all available on personal tablets (Haleem et al., 2022; Timotheou et al., 2023). As previously noted, for diagram drawing, many digital tools (such as XMind, Microsoft Visio, and xGraph) have greatly facilitated the creation of diagrams, ranging from providing basic shapes to generative AI based on user prompts (Chang et al., 2023; Moundridou et al., 2024). Many studies have reported the positive effects of technology-supported drawing on learning outcomes. These benefits encompass cognitive aspects, such as improved summarization skills (Hwang et al., 2019) and the ability to organize and connect knowledge (Gurlitt & Renkl, 2008), as well as affective aspects, which include enhanced attitudes and learning satisfaction (Hsu, 2019).

However, most studies examining the impact of technology-supported drawing primarily focus on its effectiveness in shaping final learning outcomes, often overlooking its effect on the drawing process itself. Moreover, these studies typically use text-based learning strategies as control conditions, where students engage in other learning methods, such as writing summaries or simply reading (Yang et al., 2013; Hwang et al., 2019). As Leutner and Schmeck (2014) pointed out, it remains unclear whether students learn better when generating drawings in a technology-supported setting compared to traditional hand-drawing forms. While technology can reduce the need for drawing skills by providing ready-made elements, it also restricts students' potential for free expression. One study by Fiorella and Mayer (2017) examined the use of drawing strategies in different environments: taking notes on a whiteboard, on paper, and on a laptop computer. The results indicated that handwritten notes – whether on paper or a whiteboard – encouraged students to employ more drawing strategies compared to when they took notes on a computer. They suggested that in restricted environments, such as taking notes on a computer, the frequency of students utilizing drawing strategies was negatively impacted. Meanwhile, the introduction of technology does not necessarily make drawing feel easier for students. Those who are unfamiliar with digital tools may need time to learn and adapt to new technologies (Bahçekapılı, 2023; Bazelais et al., 2018). Evidence indicates that while drawing software can offer various elements and support for creating images, it does not reduce the perceived difficulty of drawing (Schmidgall et al., 2020). More importantly, many diagramming tools and platforms often provide a large number of preset templates and standardized elements. This may lead students to rely heavily on ready-made materials, resulting in overly standardized approaches to diagram construction. Students might produce diagrams that are easier to generate using technology instead of those that could best represent their ideas. Recent developments in AI-assisted drawing environments have further amplified this tendency. Although such systems can enhance visual quality and improve efficiency through automatic layout and formatting optimization, they may also constrain learners' creative decision-making. When students readily accept automatically suggested designs, the reflective and generative processes essential for learning by drawing may be diminished (Kosmyna et al. 2025; Zhang et al. 2024). Therefore, while technology-supported drawing environments increase accessibility and visual refinement, they do not necessarily deepen cognitive engagement or promote meaningful integration of ideas. Given the limited research in this area, further investigation is needed to clarify how digital and AI-assisted diagramming tools influence the drawing process, providing more informed guidance for future educational practices.

2.3 The Present Study

This study was conducted in a mathematics teacher education course. Although diagramming skills are crucial for preservice teachers' professional development, most Chinese universities do not incorporate systematic instruction on diagram creation in their core curricula. Consequently, the cultivation of these essential teaching competencies depends entirely on students' independent learning efforts.

We adopted the intervention approach proposed by Manalo and Uesaka (2016), which involves providing encouragement and subtle suggestions to help students recognize the value of diagramming strategies. We also offered necessary training in diagramming to equip them with essential declarative and procedural knowledge. More importantly, we provided the diagramming tool to a subset of students to observe the impact of this technology on their drawing process. We assessed not only the frequency of diagram usage among students but also their perceptions of diagrams, including perceived ease of use and perceived usefulness – two critical factors that influence the adoption of new practices (Davis, 1989). Furthermore, we evaluated how the technology-supported drawing environment affected the types and quality of diagrams created by students, as these factors can indicate whether students are producing diagrams that effectively integrate course content. Specifically, the following research questions guided this study:

RQ1. Does the technology-supported drawing environment enhance the spontaneity of students' diagram usage? How does it affect their perceived ease of use and perceived usefulness of diagramming strategies?

RQ2. How does the technology-supported drawing environment influence the types and quality of diagrams that students produce?

3. Method

3.1 Participants

Using *G*Power 3.1* (https://www.gpower.hhu.de) to calculate the required sample size for subsequent statistical analyses (e.g., one-way ANOVA, paired-sample t-tests), the parameters were set at $\alpha = 0.05$ and power = 0.80 (Faul et al., 2007). The effect size was determined based on previous studies (Manalo et al., 2019; Manalo & Uesaka, 2016), yielding a required sample size of 70. The participants were undergraduate students from a public university located in Jiangsu province, China. They were enrolled in a "Pedagogy" course, which had sessions held every two weeks, totaling six sessions. Each session consisted of four classes, with each class lasting 45 minutes. A total of 82 students participated in the study, consisting of 35 males and 47 females, all aged between 18 and 19 years. The participants remained in their original class groups, preserving their natural groupings. One class was randomly assigned to serve as the experimental group (N = 42), while the other class was designated as the control group (N = 40). The study protocol was reviewed and approved by the Research Ethics Committee/Institutional Review Board of Anonymous, Jiangsu, China (Approval No.:072603399). Prior to data collection, all students received an information sheet and provided written informed consent. Participation was voluntary and had no bearing on course grades or standing; students could decline or withdraw at any time without penalty. All data were de-identified before analysis and stored securely in accordance with institutional policies.

3.2 Materials

The experimental group was given access to an online drawing website called *ProcessOn* (https://www.processon.com/diagrams). After registering, students could use the platform for free. Figure 1 includes a screenshot showing the layout of the online drawing website. The website interface is in Chinese, but key features are labeled with English translations in red text. The environment features a top menu with options such as File, Edit, Select, View, Background, and functions for sharing, collaboration, and export. The toolbar provides detailed editing capabilities, allowing users to modify text style, color, size, and line styles. On the left side of the interface, various images are accessible, including basic shapes, internet icons, and user-uploaded pictures. Below, there are pre-existing templates for mind maps, flowcharts, organizational charts, and more. The central area serves as the drawing workspace. Additionally, the platform includes simple AI-assisted drawing features that offer style and layout optimization, as well as automatic diagram creation based on user prompts. In an internet-enabled setting, students can access this environment via laptops or tablets.

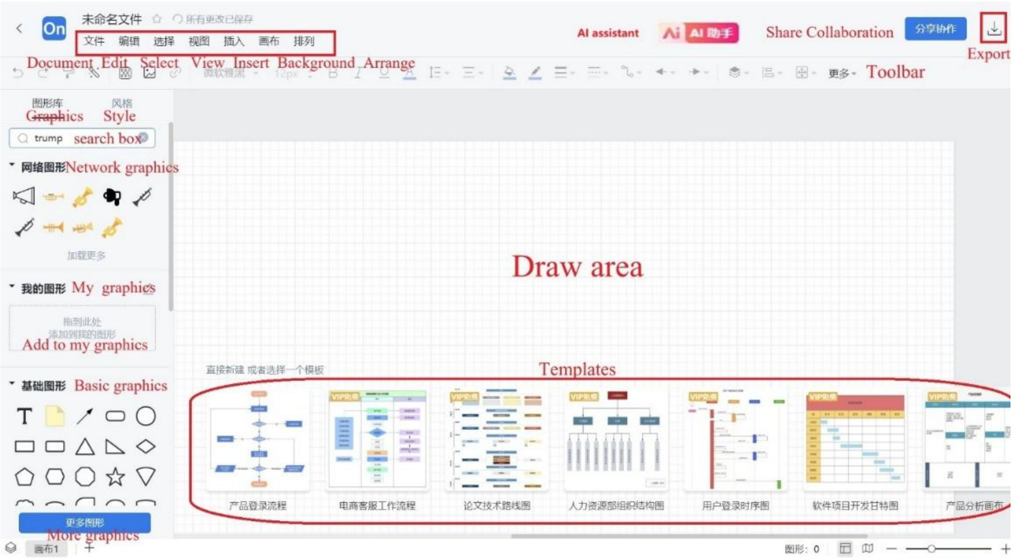


Figure 1. Screenshot of the diagramming tool interface

3.3 Measurements

In this experiment, students were required to submit course notes bi-weekly, which allowed us to observe the proportion, types, and quality of diagrams they used spontaneously.

Bi-weekly Homework: students were asked to submit an explanatory note every two weeks. They needed to choose one or two key points they learned in class and explain them. Additionally, they were informed that their explanations should be sufficiently thorough (i.e., readers should fully understand them without needing prior technical knowledge and any additional clarification). According to the course schedule, there were a total of six assignments.

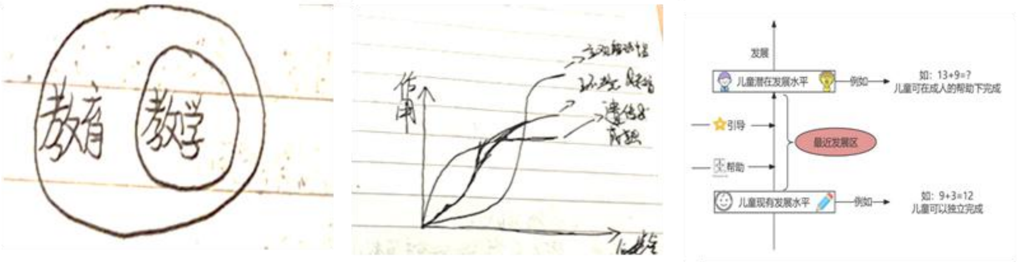
Diagram Perception Questionnaire: We adapted Davis's (1989) questionnaire, which included 6 items on perceived usefulness and 6 items on perceived ease of use. All items were presented using a 5-point Likert-type scale. The Cronbach's α analysis results were 0.984 and 0.845, respectively, meeting the required standards.

Diagram Classification Framework: In this study, a diagram was defined as any representation produced by the students, excluding representations solely in the form of words, sentences, formulae, or numbers. We referred to some diagram classification frameworks from previous studies (Engelhardt & Richards, 2018; Manalo & Fukuda, 2021) while also adjusted the categories we used based on the students' actual products. For example, if a certain category did not align with any of the students' works, it was considered for removal. Ultimately, we identified 6 distinct types. Figure 2 provides a brief description and examples of each type of diagram.

a. Diagrams related to depicting form (e.g., pictograms, schema)

b. Diagrams related to linking (e.g., flow chart, family tree, simple acting arrow)

c. Diagrams related to highlighting or marking（e.g., underlining, five-point star)



d. Diagrams related to grouping (e.g., Venn diagram)

e. Diagrams related to scaling (e.g., quantitative attributes of entities, bar chart, curve chart)

f. Combinations

Figure 2. Diagram Categories that were identified

Diagram Quality Rubric: The design of the rubric was based on previous research (e.g., Manalo & Fukuda, 2024; Moody, 2007) and was developed in consultation with some experts in the relevant field. Before formal evaluation, we piloted the rubric to ensure that the scoring criteria were clear and reliable. The rubric consisted of three evaluation dimensions: *Coverage*, which assessed whether the diagram comprehensively included the key points of the course content portrayed; *Accuracy*, which evaluated the extent to which the diagram accurately and effectively conveyed the intended meaning of the content; and *Appearance*, which examined the overall harmony, layout, and aesthetic appeal of the visual elements. Each dimension included four scoring levels, with a maximum possible score of 12 points. A detailed version of the rubric can be found in the Appendix.

3.4 Procedure

As mentioned earlier, the course comprised six biweekly sessions. At both the beginning and the end of the course, students from both the experimental and control groups completed the diagram perception questionnaire. Additionally, they were required to submit their course notes every two weeks. During the first three sessions, the instructor did not provide any guidance or training on diagrams, allowing us to observe the students' initial level of diagram usage.

In the fourth session, we conducted an intervention that lasted two class periods (approximately 90 minutes). During this intervention, we introduced both groups to the various applications of diagrams and used cases to help students understand the difference in explanations when diagrams were used versus when they were not. This approach was intended to help them appreciate the usefulness of diagrams. We also introduced students to different types of diagrams and their corresponding application scenarios.

These steps taken were the same for both the experimental and control groups. However, during the final practice phase, we provided the experimental group with access to the drawing platform *ProcessOn* and offered the necessary operational guidance, enabling them to create specific diagrams using this tool. For the control group, we presented students with various hand-drawn sketches, including figures of people, schools, books, and other basic shapes, while also offering related drawing techniques. Students were encouraged to practice creating these diagrams.

Before the start of each subsequent session (specifically during the fifth and sixth weeks), we showcased approximately 4-5 high-quality examples from students' homework as feedback. It is important to note that we informed students that the use of diagrams in their homework would not be included in their course grades. In other words, students created diagrams voluntarily, rather than for the purpose of improving their course scores.

3.5 Data Analysis

In the bi-weekly homework assignments, any student who missed three consecutive assignments had their data excluded from the analysis. Additionally, students who did not complete the required pre-test or post-test questionnaires were also excluded. Consequently, the experimental group had 37 valid samples, while the control group had 35 valid samples. The first author and a research colleague, who was initially unaware of the purpose and details of this study, independently coded the data. Any disagreements were resolved by a third researcher. The inter-coder reliability for diagram usage, diagram type, and scoring ranged from 84.5% to 96.9%, indicating a high level of scoring reliability. All data were imported into SPSS 27.0 for further analysis. In addition to basic descriptive statistics, we utilized paired-sample t-tests and one-way ANCOVA to analyze continuous data, such as students' perceptions of diagrams and the quality of the diagrams. For categorical data analysis, we employed Cochran's Q test and Pearson's chi-square test. Specifically, Cochran's Q test is a statistical procedure used to assess the consistency of proportions across multiple groups in a dichotomous dataset. It was used to analyze whether there were differences in the proportion of students using diagrams across multiple assignments (Aslam, 2023). Pearson's chi-square test was mainly used to examine whether there were differences in the distribution of diagram types before and after the intervention.

3.6 Results

3.6.1 Effects of a technology-supported drawing environment on the spontaneity of students' diagram use

The proportions of students using diagrams in their assignments for the two groups are displayed in Figure 3 below. Before the intervention (times 1-3), the rate of diagram usage remained relatively stable, fluctuating around 50%. Cochran's test indicated no significant changes in the proportion of diagram use in both groups ($p < .05$), suggesting that the influence of different content topics on students' diagram usage was minimal. However, after the intervention, reflected in the 4th assignment, the number of students using diagrams increased significantly in both groups, reaching 83.8% in the experimental group, while the control group also showed an increase to 80%. Both groups achieved a significantly higher level of diagram use compared to the first three assignments ($p < .05$), indicating that the intervention was effective for both groups. Finally, we analyzed the assignments from times 4-6 to assess whether students maintained their use of diagrams. The results showed no difference within the experimental group ($Q = 1.286$, $df = 2$, $p > .05$), indicating that the proportion of diagram usage remained stable in this group. In contrast, the control group displayed a significant difference in the subsequent assignments ($Q = 6.118$, $df = 2$, $p < .05$), suggesting a significant fading effect. Overall, in the absence of technological support, a combined intervention of verbal encouragement and teaching diagram skills was insufficient to sustain students' spontaneous use of diagrams. In contrast, a technology-supported drawing environment enhances the likely maintenance of students' spontaneous use of diagrams.

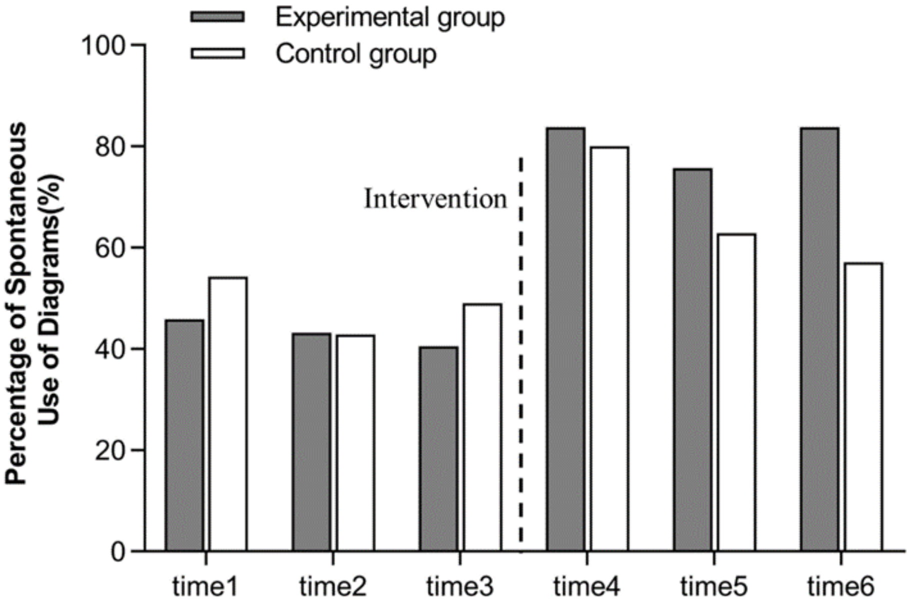


Figure 3. Diagram utilization analysis across assignments

3.6.2 Effects of a technology-supported drawing environment on students' perceptions of diagrams

The analysis of students' perceptions of diagrams is summarized in Table 2. The paired sample t-test results indicate that both the experimental and control groups showed significant improvements in perceived usefulness (*p* < .05) and perceived ease of use (p < .05) after the intervention, with the experimental group achieving particularly significant levels (*p* < .001). These findings imply that the intervention was successful in achieving its objectives: it helped students appreciate the value of diagrams and made them realize that creating such diagrams is not as challenging as they previously believed.

Table 1. Result of the paired sample t-test for students' perceptions of diagrams

Variable	Experimental group(n=37)					Control group(n=35)				
	Pretest		Posttest		Pair t- test	Pretest		Posttest		Pair t- test
	M	SD	M	SD	t	M	SD	M	SD	t
Perceived usefulness	3.58	0.84	4.56	0.53	-6.42***	3.71	0.80	4.17	0.83	-2.28*
Perceived ease of use	3.24	0.49	3.96	0.83	-4.86***	3.67	0.88	4.15	0.81	-2.38*

* *p* < .05.
** *p* < .01.
*** *p* < .001

For further analysis, a one-way ANCOVA was conducted to examine the impact of technology introduction on students' perceptions of diagrams. The results indicated that neither the pre-test scores nor the interaction between pre-test scores and group had a significant effect on the post-test scores. Analysis revealed a significant main effect of group on perceived usefulness, $F(1,69) = 5.90$, $p < .05$, $\eta^2 = .08$. According to Cohen (1988), the cutoff values for small, medium, and large effect sizes for η^2 are 0.01, 0.06, and 0.14, respectively. Therefore, the observed effect size is considered moderate. However, for perceived ease of use, the main effect of group was not significant, *F* (1,69) = .571, *p* = .452, η^2 = .01. These results suggest that the technology-supported drawing environment did not make the drawing process easier; instead, its primary impact was in enhancing students' perception of the value of diagrams.

3.6.3 Differences in diagram types produced through technology and freehand drawing

We analyzed the types of diagrams created by the two groups of students across three assignments, both before and after the intervention. The results are presented in Table 2. Prior to the intervention, the two most commonly used diagram types among students were those related to Highlighting and Linking, which accounted for a large proportion of the diagrams. However, after the intervention, both groups of students began to create a wider variety of diagram types.

Table 2. Analysis Results of Diagram Types

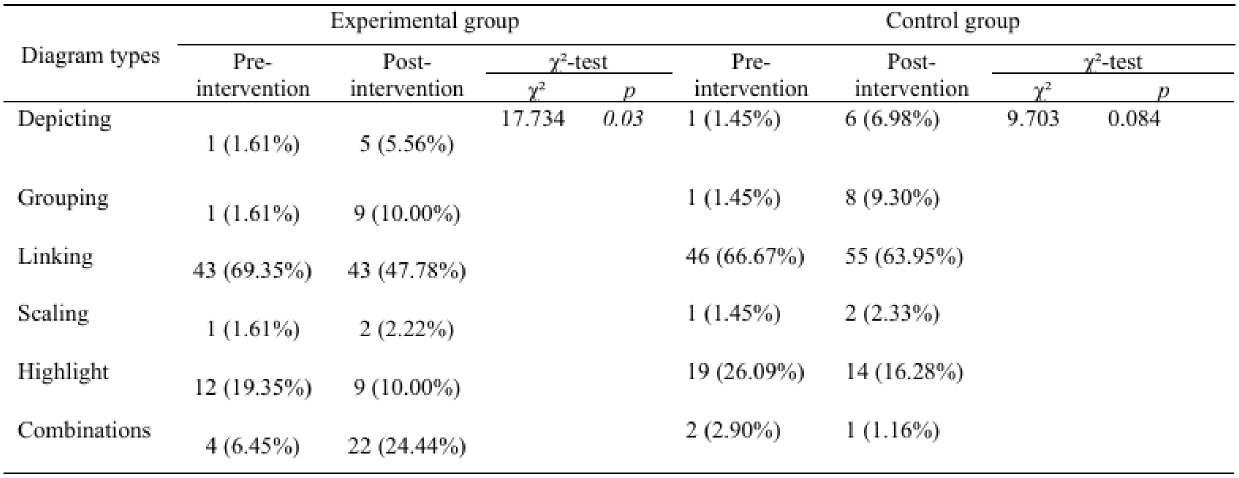


Diagram types	Experimental group				Control group			
	Pre-intervention	Post-intervention	χ^2-test		Pre-intervention	Post-intervention	χ^2-test	
			χ^2	*p*			χ^2	*p*
Depicting	1 (1.61%)	5 (5.56%)	17.734	*0.03*	1 (1.45%)	6 (6.98%)	9.703	0.084
Grouping	1 (1.61%)	9 (10.00%)			1 (1.45%)	8 (9.30%)		
Linking	43 (69.35%)	43 (47.78%)			46 (66.67%)	55 (63.95%)		
Scaling	1 (1.61%)	2 (2.22%)			1 (1.45%)	2 (2.33%)		
Highlight	12 (19.35%)	9 (10.00%)			19 (26.09%)	14 (16.28%)		
Combinations	4 (6.45%)	22 (24.44%)			2 (2.90%)	1 (1.16%)		

Further analysis using Pearson's chi-square test indicated a significant difference in the distribution of diagram types before and after the intervention in the experimental group，χ^2 (5) = 17.734，*p* < .05. In contrast, no significant difference was observed in the control group, χ^2 (5)= 9.703，*p* > .05. These findings suggest that the technology-supported drawing environment encouraged students to produce a more diverse range of diagrams. Notably, the proportion of diagrams related to Combinations in the experimental group increased from 6.45% before the intervention to 24.44% afterward. We speculate that the diagramming platform used in the experiment may have facilitated the creation of more integrative and structured diagrams.

3.6.4 Differences in the quality of diagrams produced through technology and hand-drawing

To assess changes in students' diagram drawing performance, we calculated the average scores from the first three and last three assignments to represent pre- and post-intervention levels, respectively, and then performed paired-sample t-tests. The results are summarized in Table 3. In terms of overall quality, no significant changes were found in either group following the intervention (*p* > .05). Regarding the sub-dimensions of the quality of the diagrams, students in the experimental group showed significant improvement in the Appearance dimension of their diagrams (*t* = -3.21, *p* < .01). In contrast, the control group demonstrated a clear improvement in the Accuracy dimension after the intervention (*t* = -3.608, *p* < .01). For the Coverage dimension, neither group evidenced any significant changes following the intervention (*p* > .05).

Table 3. Paired-sample t-test results for diagram quality

Dimension	Experimental group						Control group					
	Pre-intervention		Post-intervention		Pair t- test		Pre-intervention		Post-intervention		Pair t- test	
	M	SD	M	SD	t	diff.	M	SD	M	SD	t	diff.
Overall	6.53	2.07	7.48	1.46	-1.97	n.s.	6.32	2.03	6.42	1.29	-0.27	n.s.
Coverage	2.27	0.93	2.41	0.63	-0.64	n.s.	2.50	1.03	2.24	0.64	1.17	n.s.
Accuracy	2.24	0.72	2.51	0.54	-1.59	n.s.	1.95	0.75	2.51	0.44	-3.61**	Post>Pre
Appearance	2.01	0.70	2.55	0.62	-3.21**	Post>Pre	1.87	0.65	1.67	0.55	1.22	n.s.

* $p < .05$.
** $p < .01$.
*** $p < .001$

Four separate one-way ANCOVAs (Table 4) were conducted to examine the effect of the drawing condition (technology-supported vs. hand-drawn) on diagram scores for overall quality and its sub-dimensions (Coverage, Accuracy, Appearance), treating the corresponding pre-intervention diagram scores as covariates. All four results indicated that neither the covariates nor their interaction with the group had a significant effect on the post-intervention diagram scores. The main effect analysis revealed significant differences in overall quality between the groups, F (1, 53) = 7.840, $p < .01$, $\eta^2 = .129$. According to Cohen (1988), this effect size is considered moderate. In terms of specific sub-dimensions, group effects were not significant for Coverage and Accuracy; however, for the Appearance dimension, the group effect was significant, F (1, 53) = 30.722, $p < .001$, $\eta^2 = .367$, indicating a large effect size (Cohen, 1988). These findings suggest that a technology-supported drawing environment can enhance students' diagram quality, primarily by improving the visual aesthetics of the diagrams. However, it does not contribute to increasing the coverage of knowledge points in the diagrams or improving the accuracy of meaning conveyed.

Table 4. ANCOVA results for diagram quality

Dimension	Experimental group	Control group	ANCOVA		
	Adjusted M	Adjusted M	F	η^2	Post hoc
Overall	7.47	6.43	7.840**	.129	Experimental group>Control group
Coverage	2.42	2.24	0.002	.019	n.s.
Accuracy	2.50	2.52	0.007	.001	n.s.
Appearance	2.55	1.67	30.722***	.367	Experimental group>Control group

* $p < .05$.
** $p < .01$.
*** $p < .001$

4. Discussion

This study explored a frequently overlooked issues: the effect of digital diagramming tools on students' drawing practices. The results suggest that the use of technology in the drawing process brought about several meaningful changes. It appeared to shift students' understanding of diagrams, led to more spontaneous use of diagrams during learning, and contributed to improved diagram quality. The following discussion will explore these aspects in more detail.

For RQ 1, we found that students in the experimental group maintained a high usage rate of diagrams after the intervention. In contrast, students in the control group showed a significant increase in diagram usage immediately after the intervention, but their use of diagrams gradually declined in subsequent assignments. This suggests that a technology-supported drawing environment enhances students' spontaneity in creating diagrams, which aligns with research by Lorenz et al. (2019), where they discovered that students showed greater engagement when producing computer-assisted drawings. Furthermore, we found that the technology-supported drawing environment significantly increased students' perceptions about the usefulness of diagrams. One possible reason for this is that diagrams created with diagramming tools appear more visually appealing and realistic, resembling those found in journals and lectures. This makes it easier for students to recognize the value of using diagrams in their future work. In contrast, hand-drawn diagrams often look like rough sketches, which, while useful for personal learning, may not immediately convey their broader value to students. However, in terms of perceived ease of use, a technology-supported drawing environment did not yield positive effects. This finding aligns with the study by Schmidgall et al. (2020). In their research, they provided two types of support using tablets: local support (offering pre-drawn individual shape elements) and global support (providing an overall background for arranging elements). Their results showed that neither type of support reduced students' perceived difficulty compared to freehand drawing. There may be two possible reasons for this. From the perspective of the drawing process itself, van Meter and Garner's (2005) Generative Theory of Drawing Construction (GTDC) suggests that the drawing process requires learners to extract key information from the text and construct a coherent verbal representation of that information. Additionally, they must integrate this representation meaningfully with non-verbal (visual) representation. This process is challenging for learners because it involves selecting, organizing, and transforming information. In a technology-supported drawing environment, even when ready-made shapes and layouts are provided, students still need to convert textual content into visual representations. They must mentally imagine complex visuo-spatial objects and their relationships. Furthermore, to externalize these representations, students need to align the mental images that arise in their minds with the elements and layouts available on the diagramming platform. This often requires multiple adjustments and transformations of existing elements and layouts to match their mental image (Kosslyn, 1994). From the perspective of technology usage, while technology-supported drawing alleviates concerns about drawing skills, the trade-off is that students must learn to master the technical operations of the tools. Some studies have highlighted issues such as the extraneous cognitive load associated with human-computer interaction (Skulmowski & Xu, 2022) and computer anxiety (Abdullah & Ward, 2016). These challenges may lead students to perceive technology-supported drawing as more complex than easy to use.

RQ 2, we found that the types of diagrams students created in a technology-supported drawing environment differed from those produced in a hand-drawn setting. This finding extends the study by Manalo and Fukuda (2021), which only examined the types of diagrams generated under hand-drawn conditions and did not compare them with those created in a technology-supported environment. Additionally, we observed that students using diagramming tools seemed more inclined to create Combination type diagrams. Based on the works of students in the experimental group, we speculate that this may be due to a sense of novelty, prompting them to experiment with the tool's functionalities. They frequently added various shape elements to their diagrams and attempted to integrate different templates, even when some elements were redundant. This tendency was also reflected in our subsequent diagram quality analysis. Although the diagrams created by the experimental group were visually more refined than those from the control group, there was no significant difference in terms of coverage or accuracy. This suggests that while diagrams produced with technology may appear more complex and integrative of various diagram types, they do not necessarily contain more information or enhance the effectiveness of information transmission. This finding complements the study by Cromley et al. (2020) and helps explain why technology-supported drawing does not significantly enhance students' learning outcomes compared to hand-drawn diagrams. While diagramming tools improve aesthetics – such as layout and color – they do not assist students in extracting key information or establishing a strong connection between the visual elements and the content being conveyed. These processes, which involve deep information processing and comprehension, are essential for drawing strategies to positively impact learning outcomes (Schmidgall et al., 2019; Schwamborn et al., 2010). However, it is important to note that diagrams are not only intended to facilitate personal learning; they also serve a communicative function (Manalo & Uesaka, 2014). In communicative contexts, visually appealing diagrams can effectively capture the audience's attention. From this perspective, diagramming tools offer considerable benefits.

5. Limitations

One significant limitation of this study is that the participants were mainly university students, and the tasks were informal take-home assignments with no time constraints. These factors may have affected the results. However, this reflects their authentic diagram usage patterns in natural learning contexts, especially in homework. Future research could include students from other educational levels, such as elementary, middle, and high school, and examine the impact of diagramming tools on the drawing process under more formal task conditions. Additionally, future studies could further identify the challenges students face when creating diagrams in a technology-supported environment. Methods such as think-aloud protocols and video recordings could be employed for more in-depth analysis. These investigations would be valuable for designing effective interventions to help students spontaneously create high-quality diagrams.

6. Conclusions

Given the educational potential of learning by drawing and the increasing integration of ICT in classrooms (such as laptops and tablets), this study examined the impact of a technology-supported drawing environment – specifically a platform for creating diagrams – compared to a traditional hand-drawn condition. It explored how this environment influenced students' spontaneity in using diagrams, their perception of diagrams, and the diversity and quality of the diagrams they created. Overall, the introduction of technology had a positive effect. It enhanced students' spontaneous use of diagrams, making them more aware of the value of diagrams. Additionally, we observed that technology-supported drawing environments can enhance students' diagram quality, primarily by improving the visual aesthetics of the diagrams. However, they do not contribute to increasing the coverage of knowledge points in the diagrams or to improving the accuracy of meaning conveyed. In future educational practices, teachers might consider incorporating relevant drawing software when teaching diagram strategies. This approach can encourage students to apply these strategies more spontaneously. In this process, teachers should not only focus on teaching operational skills but also guide students on how to extract key information from the text and choose appropriate visual elements to represent them. The development of these skills will likely contribute to their future academic and professional success.

Appendix A

Diagram Quality Rubric

Dimension	Description	Points
Coverage	The diagram fully covers all major points of the selected content without any obvious omissions.	4
	The diagram covers most major points of the selected content. While most essential aspects are addressed, there may be some minor omissions.	3
	The diagram covers only a small portion of the selected content, with many essential points and details omitted.	2
	The diagram does not cover any major points and shows no relationship to the selected content.	1
Accuracy	All elements in the diagram are accurate and complete, and their relationships are logical. The diagram effectively conveys the intended meaning of the selected content.	4
	Most elements in the diagram are accurate and complete. Relationships are mostly logical, though there may be some minor issues in conveying the intended meaning of the selected content.	3
	Some elements in the diagram are incorrect or incomplete, and relationships are unclear or problematic. This causes some confusion in conveying the intended meaning of the selected content.	2
	Many elements are incorrect or incomplete, and relationships are confusing or incorrect. This results in a serious misinterpretation of the intended meaning of the selected content.	1
Appearance	The diagram is visually appealing and highly engaging. Colors, text, and shapes are well coordinated. Labels are clear, and the layout is uncluttered and aesthetically pleasing, enhancing readability.	4
	The diagram is generally attractive and engaging. Colors, text, and shapes are mostly coordinated with minor inconsistencies. Labels are mostly clear, and the layout is mostly uncluttered, with good readability, though a few parts may be unclear.	3
	The diagram has some visual issues affecting its appeal. Colors, text, and shapes may lack coordination. Labels may be unclear, and the layout may be somewhat cluttered. Readability is somewhat low, requiring extra effort to understand.	2
	The diagram is visually unappealing and disengaging. Colors, text, and shapes are inconsistent or inappropriate. Labels are hard to read, and the layout is cluttered and confusing. Readability is poor, requiring significant time and effort to interpret.	1

References:

Abdullah, F., & Ward, R. (2016). Developing a general extended technology acceptance model for e-learning (GETAMEL) by analysing commonly used external factors. Computers in Human Behavior, 56, 238–256. https://doi.org/10.1016/j.chb.2015.11.036

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. Science, 333(6046), 1096–1097. https://doi.org/10.1126/science.1204153

Aslam, M. (2023). Cochran's q test for analyzing categorical data under uncertainty. Journal of Big Data, 10(1), 147. https://doi.org/10.1186/s40537-023-00823-3

Bahçekapılı, E. (2023). Predicting the secondary school students' intention to use e-learning technologies. Research in Learning Technology, 31, 2881. https://doi.org/10.25304/rlt.v31.2881

Bazelais, P., Doleck, T., & Lemay, D. J. (2018). Investigating the predictive power of TAM: A case study of CEGEP students' intentions to use online learning technologies. Education and Information Technologies, 23(1), 93–111. https://doi.org/10.1007/s10639-017-9587-0

Chang, C.-C., Hwang, G.-J., & Tu, Y.-F. (2023). Roles, applications, and trends of concept map-supported learning: A systematic review and bibliometric analysis of publications from 1992 to 2020 in selected educational technology journals. Interactive Learning Environments, 31(9), 5995–6016. https://doi.org/10.1080/10494820.2022.2027457

Chang, C.-J., Liu, C.-C., & Tsai, C.-C. (2016). Supporting scientific explanations with drawings and narratives on tablet computers: An analysis of explanation patterns. The Asia-Pacific Education Researcher, 25(1), 173–184. https://doi.org/10.1007/s40299-015-0247-0

Cromley, J. G., Du, Y., & Dane, A. P. (2020). Drawing-to-learn: Does meta-analysis show differences between technology-based drawing and paper-and-pencil drawing? Journal of Science Education and Technology, 29(2), 216–229. https://doi.org/10.1007/s10956-019-09807-6

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319–340. https://doi.org/10.2307/249008

Engelhardt, Y., & Richards, C. (2018). A framework for analyzing and designing diagrams and graphics. In P. Chapman, G. Stapleton, A. Moktefi, S. Perez-Kriz, & F. Bellucci (Eds.), Diagrammatic representation and inference. Diagrams 2018. Lecture notes in artificial intelligence, 10871 (pp. 201–209). Springer. https://doi.org/10.1007/978-3-319-91376-6_20

Erdogan, Y. (2009). Paper-based and computer-based concept mappings: The effects on computer achievement, computer anxiety and computer attitude. British Journal of Educational Technology, 40(5), 821–836. https://doi.org/10.1111/j.1467-8535.2008.00856.x

Farrokhnia, M., Pijeira-Díaz, H. J., Noroozi, O., & Hatami, J. (2019). Computer-supported collaborative concept mapping: The effects of different instructional designs on conceptual understanding and knowledge co-construction. Computers & Education, 142, 103640. https://doi.org/10.1016/j.compedu.2019.103640

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175–191. https://doi.org/10.3758/BF03193146

Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. Educational Psychology Review, 28(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9

Fiorella, L., & Zhang, Q. (2018). Drawing boundary conditions for learning by drawing. Educational Psychology Review, 30(3), 1115–1137. https://doi.org/10.1007/s10648-018-9444-8

Gijlers, H., Weinberger, A., Van Dijk, A. M., Bollen, L., & Van Joolingen, W. (2013). Collaborative drawing on a shared digital canvas in elementary science education: The effects of script and task awareness support. International Journal of Computer-Supported Collaborative Learning, 8(4), 427–453. https://doi.org/10.1007/s11412-013-9180-5

Gurlitt, J., & Renkl, A. (2008). Are high-coherent concept maps better for prior knowledge activation? Differential effects of concept mapping tasks on high school vs. university students. Journal of Computer Assisted Learning, 24(5), 407–419. https://doi.org/10.1111/j.1365-2729.2008.00277.x

Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. Sustainable Operations and Computers, 3, 275–285. https://doi.org/10.1016/j.susoc.2022.05.004

Heckler, A. F. (2010). Some consequences of prompting novice physics students to construct force diagrams. International Journal of Science Education, 32(14), 1829–1851. https://doi.org/10.1080/09500690903199556

Hsu, T.-C. (2019). Using a concept mapping strategy to improve the motivation of EFL students in google hangouts peer-tutoring sessions with native speakers. Interactive Learning Environments, 27(2), 272–285. https://doi.org/10.1080/10494820.2018.1463268

Hwang, G., Chen, M. A., Sung, H., & Lin, M. (2019). Effects of integrating a concept mapping-based summarization strategy into flipped learning on students' reading performances and perceptions in Chinese courses. British Journal of Educational Technology, 50(5), 2703–2719. https://doi.org/10.1111/bjet.12708

J Jackel, B. (2014). Towards a general diagrammatic literacy: An approach to thinking critically about diagrams. In T. Dwyer, H. Purchase, & A. Delaney (Eds.), Diagrammatic representation and inference. Lecture notes in computer science, 8578 (pp. 64–70). Springer. https://doi.org/10.1007/978-3-662-44043-8_11

Kosslyn, S. M. (1994). Image and brain: The resolution of the imagery debate. The MIT Press.

Kosmyna, N., Hauptmann, E., Yuan, Y. T., Situ, J., Liao, X.-H., Beresnitzky, A. V., Braunstein, I., & Maes, P. (2025). Your brain on ChatGPT: Accumulation of cognitive debt when using an AI assistant for essay writing task [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2506.08872

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. Cognitive Science, 11(1), 65-99. https://doi.org/10.1016/S0364-0213(87)80026-5

Leopold, C., Sumfleth, E., & Leutner, D. (2013). Learning with summaries: Effects of representation mode and type of learning activity on comprehension and transfer. Learning and Instruction, 27, 40–49. https://doi.org/10.1016/j.learninstruc.2013.02.003

Leutner, D., & Schmeck, A. (2014). The generative drawing principle in multimedia learning. In R. E. Mayer (Ed.), The Cambridge handbook of multimedia learning (3rd ed., pp. 433–448). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.022

Lorenz, L. A. (2019). Computer-based visualizing: Learning from science texts by means of self-generated computer-based drawings [Doctoral dissertation, University of Duisburg-Essen]. DuEPublico. https://doi.org/10.17185/DUEPUBLICO/70107

Luna-Gijón, G., Nava-Cuahutle, A. A., & Martínez-Cantero, D. A. (2025). The visual diagram: An information design tool for science communication. Journal of Visual Literacy, 44(1), 18–44. https://doi.org/10.1080/1051144X.2025.2462383

Manalo, E., & Fukuda, M. (2021). Diagrams in essays: Exploring the kinds of diagrams students generate and how well they work. In A. Basu, G. Stapleton, S. Linker, C. Legg, E. Manalo, & P. Viana (Eds.), Diagrammatic representation and inference. Diagrams 2021. Lecture Notes in Artificial Intelligence, 12909 (pp. 553–561). Springer. https://doi.org/10.1007/978-3-030-86062-2_56

Manalo, E., & Fukuda, M. (2024). Integration of learning through the use of self-constructed diagrams: Opportunities and challenges. In Lemanski, J., Johansen, M. W., Manalo, E., Viana, P., Bhattacharjee, R., & Burns, R. (Eds.). (2024). Diagrammatic representation and inference. Diagrams 2024. Lecture Notes in Artificial Intelligence, 14981 (pp. 358-365). Springer. https://doi.org/10.1007/978-3-031-71291-3_29

Manalo, E., Tsuda, A., & Dryer, R. (2019). The effect of cultivating diagram use on the quality of EFL students' written explanations. Thinking Skills and Creativity, 33, 100588. https://doi.org/10.1016/j.tsc.2019.100588

Manalo, E., & Uesaka, Y. (2014). Students' spontaneous use of diagrams in written communication: Understanding variations according to purpose and cognitive cost entailed. In T. Dwyer, H. Purchase, & A. Delaney (Eds.), Diagrammatic representation and inference. Diagrams 2014. Lecture notes in computer science, 8578 (pp. 78–92). Springer. https://doi.org/10.1007/978-3-662-44043-8_13

Manalo, E., & Uesaka, Y. (2016). Hint, instruction, and practice: The necessary components in promoting spontaneous diagram use in students' written work? In M. Jamnik, Y. Uesaka, & S. Elzer Schwartz (Eds.), Diagrammatic representation and inference. Diagrams 2016. Lecture Notes in Artificial Intelligence, 9781 (pp. 157–171). Springer. https://doi.org/10.1007/978-3-319-42333-3_12

Mayer, R. E., & Fiorella, L. (2021). Introduction to Multimedia Learning. In R. E. Mayer & L. Fiorella (Eds.), The Cambridge Handbook of Multimedia Learning (3rd ed., pp. 3–16). Cambridge University Press. https://doi.org/10.1017/9781108894333.003

Moody, D. (2007). What Makes a Good Diagram? Improving the Cognitive Effectiveness of Diagrams in IS Development. In W. Wojtkowski, W. G. Wojtkowski, J. Zupancic, G. Magyar, & G. Knapp (Eds.), Advances in Information Systems Development (pp. 481–492). Springer. https://doi.org/10.1007/978-0-387-70802-7_40

Moundridou, M., Matzakos, N., & Doukakis, S. (2024). Generative AI tools as educators' assistants: Designing and implementing inquiry-based lesson plans. Computers and Education: Artificial Intelligence, 7, 100277. https://doi.org/10.1016/j.caeai.2024.100277

Rogers, E. M. (2003). Diffusion of Innovations (5th ed.). Free Press.

Schmidgall, S. P., Eitel, A., & Scheiter, K. (2019). Why do learners who draw perform well? Investigating the role of visualization, generation and externalization in learner-generated drawing. Learning and Instruction, 60, 138–153. https://doi.org/10.1016/j.learninstruc.2018.01.006

Schmidgall, S. P., Scheiter, K., & Eitel, A. (2020). Can we further improve tablet-based drawing to enhance learning? An empirical test of two types of support. Instructional Science, 48(4), 453–474. https://doi.org/10.1007/s11251-020-09513-6

Schwamborn, A., Mayer, R. E., Thillmann, H., Leopold, C., & Leutner, D. (2010). Drawing as a generative activity and drawing as a prognostic activity. Journal of Educational Psychology, 102(4), 872–879. https://doi.org/10.1037/a0019640

Shimizu, Y. (2025). Learning engagement as moderator between self-efficacy, math anxiety, use of diagrams, and complex plane problem-solving. Eurasia Journal of Mathematics, Science and Technology Education, 21(2), em2586. https://doi.org/10.29333/ejmste/15956

Skulmowski, A., & Xu, K. M. (2022). Understanding cognitive load in digital and online learning: A new perspective on extraneous cognitive load. Educational Psychology Review, 34(1), 171–196. https://doi.org/10.1007/s10648-021-09624-7

Stull, A. T., & Mayer, R. E. (2007). Learning by doing versus learning by viewing: Three experimental comparisons of learner-generated versus author-provided graphic organizers. Journal of Educational Psychology, 99(4), 808–820. https://doi.org/10.1037/0022-0663.99.4.808

Terzian, S. (2019). The history of technology and education. In J. L. Rury & E. H. Tamura (Eds.), The Oxford Handbook of the History of Education (pp. 553–567). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199340033.013.33

Timotheou, S., Miliou, O., Dimitriadis, Y., Sobrino, S. V., Giannoutsou, N., Cachia, R., Monés, A. M., & Ioannou, A. (2023). Impacts of digital technologies on education and factors influencing schools' digital capacity and transformation: A literature review. Education and Information Technologies, 28(6), 6695–6726. https://doi.org/10.1007/s10639-022-11431-8

Uesaka, Y., & Manalo, E. (2014). How communicative learning situations influence students' use of diagrams: Focusing on spontaneous diagram construction and protocols during explanation. In T. Dwyer, H. Purchase, & A. Delaney (Eds.), Diagrammatic Representation and Inference, Diagrams 2014. 8578 (pp. 93–107). Springer. https://doi.org/10.1007/978-3-662-44043-8_14

Uesaka, Y., Manalo, E., & Ichikawa, S. (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. https://doi.org/10.1016/j.learninstruc.2007.02.006

Uesaka, Y., Manalo, E., & Ichikawa, S. (2010). The effects of perception of efficacy and diagram construction skills on students' spontaneous use of diagrams when solving math word problems. In A. K. Goel, M. Jamnik, & N. H. Narayanan (Eds.), Diagrammatic Representation and Inference, Diagrams 2010. 6170 (pp. 197–211). Springer. https://doi.org/10.1007/978-3-642-14600-8_19

Van De Werfhorst, H. G., Kessenich, E., & Geven, S. (2022). The digital divide in online education: Inequality in digital readiness of students and schools. Computers and Education Open, 3, 100100. https://doi.org/10.1016/j.caeo.2022.100100

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. Educational Psychology Review, 17(4), 285–325. https://doi.org/10.1007/s10648-005-8136-3

Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. Management Science, 46(2), 186–204. https://doi.org/10.1287/mnsc.46.2.186.11926

Wittrock, M. C. (1989). Generative processes of comprehension. Educational Psychologist, 24(4), 345–376. https://doi.org/10.1207/s15326985ep2404_2

Yang, C.-C., Hwang, G.-J., Hung, C.-M., & Tseng, S.-S. (2013). An evaluation of the learning effectiveness of concept map-based science book reading via mobile devices. Journal of Educational Technology & Society, 16(3), 167–178. JSTOR. http://www.jstor.org/stable/jeductechsoci.16.3.167

Zhang, S., Zhao, X., Zhou, T., & Kim, J. H. (2024). Do you have AI dependency? The roles of academic self-efficacy, academic stress, and performance expectations on problematic AI usage behavior. International Journal of Educational Technology in Higher Education, 21, 34. https://doi.org/10.1186/s41239-024-00467-0

Zhou, X., Smith, C. J. M., & Al-Samarraie, H. (2024). Digital technology adaptation and initiatives: A systematic review of teaching and learning during COVID-19. Journal of Computing in Higher Education, 36(3), 813–834. https://doi.org/10.1007/s12528-023-09376-z