Article

Journal of Educational Computing Research
2024, Vol. 62(4) 1035–1060

DOI: 10.1177/07356331241226594
journals.sagepub.com/home/jec

Effects of Dynamic Mathematical Software on Students' Performance: A Three-Level Meta-Analysis

Zhongtian Ji[1], Kan Guo[1], and Shuang Song[2]

Abstract

As a significant tool to integrate information technology and education, dynamic mathematical software (DMS) has been widely concerned in recent years. However, how to better apply it to instruction practice deserves further exploration. Thus, we adopted the meta-analysis method to analyze the DMS-based experiments published between 2000 and 2020. A three-level meta-analysis of data from 107 studies involving 10,507 participants and 138 effect sizes revealed a moderate effect size (d = .632, 95% CI = [.550, .713]). Moreover, moderator analyses showed that: (1) cultural background had significant moderating effects; (2) students performed better on near-transfer tests than far-transfer tests; (3) DMS used by students independently had better effects; (4) intervention duration had significant moderating effects; (5) some of the above significant moderating effects were unique after controlling for others. Overall, our findings suggest that DMS has positive effects on students' performance and teachers should be meticulous in designing their teaching plans.

Keywords

dynamic mathematical software, primary education, secondary education, three-level meta-analysis

[1]School of Mathematical Sciences, Beijing Normal University, Beijing, China
[2]College of Teacher Education, Capital Normal University, Beijing, China

Corresponding Author:
Kan Guo, School of Mathematical Sciences, Beijing Normal University, No.19, Xinjiekouwai St, Haidian District, Beijing 100875, China.
Email: guokan@bnu.edu.cn

Introduction

Applying information and technology in education is promising to improve students' abilities (Zulnaidi et al., 2020). A plethora of studies have revealed a positive effect on students' performance and attitude in some special disciplines and skills such as spatial ability (Nurjanah et al., 2020), or biology achievements (Aisah et al., 2018). Ran et al. (2022) estimated the effect of technology on students' mathematical achievement to be .23 and proposed that technology would be used more effectively when creating a communicative environment. Among educational technology, the role of dynamic mathematical software (DMS) has received increased attention across multiple subjects, which was widely used in teachers' practice rely on its interactive nature (Cekmez & Bulbul, 2018) and powerful functions, especially its multiple representations (Gokce & Guner, 2022).

Developing Functions of Dynamic Mathematical Software

The Geometers' Sketchpad and Cabri 3D have been published and used as the most original dynamic geometry software (DGS) in the 1990s (Bantchev, 2010), which was found to be adequate for teachers in class to draw some geometric models (Guven & Kosa, 2008; Nordin et al., 2010), promoting students' more intuitive characterization and understanding of mathematical concepts. The last twenty years have witnessed a growing pedagogic interest in these software, many new forms, collectively referred to as DMS, have come a long way in their strides for different periods of schooling and different fields in education. For instance, the research conducted by Aisah et al. (2018) used GeoGebra to describe the process of protein synthesis in DNA to explore the relationship between the triplets. Ciobanu et al. (2022) discussed the application of GeoGebra in learning oscillatory motion. In summary, today's DMS can provide a variety of external representations such as graphs, figures, and tables. Additionally, GeoGebra had great potential for integration into personalized learning practices such as e-learning (Albano & Dello Iacono, 2019) and flipped classroom (Salas-Rueda, 2021). To date, DMS has been shown to effectively connect not only geometry but also fields such as algebra in mathematics, some other related disciplines (e.g., physics), and even far-transfer on students' universal skills including critical thinking (Munandar et al., 2020), and high-order thinking skills (Misrom et al., 2020). Various software has broken through the application scenario only can be operated on computers, but also be run and used on more convenient handheld devices such as iPad and smartphones (Pankova & Hanc, 2019).

Educational Practice Based on Dynamic Mathematical Software

The application of DMS in education may have various effects on the outcomes of different research methods and issues from a variety of domains (Ulusoy & Turus, 2022). A promising way to optimize the entire process of teaching is to integrate DMS into the teaching plan. For example, in a study by Birgin and Topuz (2021), the learning environment with GeoGebra significantly increased secondary school students' attitudes toward geometry. Aksu and Zengin (2022) pointed out clearly that students' representations would evolve in the dynamic mathematical environment, and that contributes to the ability of mathematical reasoning. Despite the potential of DMS, studies have yielded mixed results in educational practice. Yan (2018) found that sixth-grade students were treated by DMS on geometry learning, but there was no significance between the experimental group and the control group in their post-test. It seemed that students need to dedicate certain attention resources and mental efforts to understand these representations DMS provided. Based on representational flexibility, some of the student's specific abilities (e.g., having the necessary diagrammatic knowledge to interact with the representations) related to the effect used external representation to support learning. The environment characteristics and several sociocultural factors could affect students' representational choices. Only if they mastered the rule about how to use the representation and relate them to other situations could they benefit from using it. In view of the importance of DMS, knowing how best to create the environment for heightening the actual effect is a tough task (Cayton et al., 2017).

Based on its interactive nature, Romero Albaladejo et al. (2015) indicated that social interaction was the essential factor to promote students' progress. Basic classroom norms which facilitated explanation and the use of representations should be formulated by teachers and students. In such a dynamic mathematical environment, students' interactions with their classmates and teachers induced the emergence of varied collaborative behaviors and socially mediated metacognitive processes, fostering the co-construction and development of problem-solving strategies (Hegedus & Otalora, 2023). Thus, implications might be ruined if teachers were the main body of DMS because that would reduce interaction and communication among students (Stein et al., 1996). However, the recommended age or school level for students to use technology was another complicated issue (Jancheski, 2019). Students' prior knowledge (e.g., conceptual knowledge) affected their ability to convert and assimilate external representations, which related to the effectiveness of DMS. As a teaching and learning tool, DMS was advised to accommodate the cognitive development of students (Widodo et al., 2017).

Similarly, the issue of the use duration has also received considerable attention. Duration has been shown significant influence on the effect of such educational technologies (Li & Ma, 2010). Since DMS has integrated multiple functions in diverse domains, it seems to be suitable in every class. Providing students with a long-term DMS environment and active guidance might improve their representative thinking and make them more flexible. Nevertheless, data from several studies revealed that applying computer technology to front-line education for a shorter time was surely a wiser choice. It was noteworthy that the novelty effect (Chan & Leung, 2014) and the Hawthorne effect (Juandi et al., 2021) could not be ignored during the implementation practice. What's more, it might be closely related to how teachers maintained combining their lesson plans with technologies (Hlalele, 2020) and whether sufficient teaching resources available were supported by their school or the local government (Ran et al., 2022). Taken together, these studies highlight the complexity of intervention time, not only when to use DMS, but go deep into how long is better.

Considering the constraint time and other factors, to address educators' concerns, it is hoped that this research will contribute to a profound understanding of the effects of transfer and sustainability. A major expectation is that students will have the capability to transfer what they have mastered to other similar situations and the real-life world (Rahimi et al., 2022). Ubuz et al. (2009) found that the effect of DMS on students' performance was decreased in their delayed posttest. But Wang (2016) reported that there existed not much difference in students' performance on the far-transfer tests and near-transfer tests. Besides, more holistic research studies on the use of all DMS were suggested to be explored to reveal the effects, advantages, and disadvantages of this technology in education (Gokce & Guner, 2022). By focusing more on interactive and dynamic environments, the results will be more general without the limitation of several functions of one particular software.

To clarify these above issues, further meta-analysis is needed to examine the impact of DMS and develop reliable methods for educators to use the software. In 2014, Chan and Leung (2014) conducted a meta-analysis that evaluated the effect of DGS-based instruction in terms of improving students' mathematical achievement ($d = 1.02$). However, only nine quasi-experimental studies were included. More recently, Juandi et al. (2021) reported a meta-analysis of studies conducted in Indonesia ($n = 29$) and estimated the effect size of GeoGebra software on math ability to be .96. In summary, although past studies have proved the effect of DMS, insufficient numbers of sample and specified subject theme formed its limitations. Research has yet to systematically figure out how to apply DMS properly to more general instruction practice. Additionally, a question for this research is that one study may conduct two post-tests after the class and term. Consequently, the common method of selecting one effect size per study in the traditional meta-analysis does not apply to this study (Ji & Guo, 2023). All the useful information could be extracted by adopting the method of the three-level meta-analytic model (Assink & Wibbelink, 2016). Till now, no previous study has used the three-level meta-analysis model for analyzing the effect of DMS on school education.

The Present Study

The purpose of this meta-analysis is to synthesize quantitatively the impact of DMS intervention on improvement and achievements of school students, and the factors that may influence their effectiveness. Specifically, we asked the following questions:

Q1. What is the size of the effect of DMS interventions on students' performance?
Q2. Does the participant's characteristics (students' school level, students' cultural background) account for some of the variability in the effects of interventions?
Q3. Does the effect vary as a function of (a) type of DMS, (b) users of DMS, (c) intervention duration, or (d) transfer test?

Method

Data Collection

The data collection, coding procedures, and inclusion criteria were outlined in Figure 1. To select studies for the three-level meta-analysis, we first searched computerized databases (i.e., Web of Science, Scopus, ERIC, ProQuest Educational, and the China National Knowledge Infrastructure) for studies published between 2000 and 2020. We first used the terms "dynamic mathematical software" and "dynamic geometry software" and used the OR command. After reading those studies, the following common DMS was used in our search: "GeoGebra", "Cabri 3D", "Hawgent", "Sketchpad" and "Autograph". We removed the duplicates at first and contacted researchers who published studies that we could not find and asked for their papers or unpublished data.

Operation Criteria for Inclusion and the Elimination of Studies

Once we identified the potential research, we read the abstracts and eliminated any studies which introduced the application of DMS only or research that was described as qualitative, a case study, or a review. Next, we carefully read the Method and Result section, ensuring the studies met the following criteria: (a) Studies must employ an experimental or quasi-experimental design and report necessary data to calculate the effect size, (b) Studies from primary school, junior high school, and general high school were included. For communication, studies could have been conducted in any country, but only written in English-language or providing a partial translation in English where the methods and results were clearly described (Weng et al., 2023). Furthermore, if a thesis was published as a journal article, we only considered the article itself (Georgiou et al., 2020). After applying these criteria, we identified 107 studies with sample sizes ranging from 39 to 345.

Coding Procedures

All studies were double-coded and 100% interrater agreement was achieved (supplementary file available from the corresponding author upon reasonable request). We coded the following content of the selected studies separately: (a) author name; (b) the year of publication; (c) sample size; (d) school level; (e) country/region; (f) type of DMS; (g)user of DMS; (h) intervention duration; (i) transfer test. Based on the basic rules of three-level meta-analysis, all effect sizes in studies were then coded. The consensus rate (Cohen's kappa) varied between 90% and 100%. Most differences in coding were due to the lack of information provided in several studies.

Moderator Variables

Participant Characteristics. The school level of participants was coded into three categories: primary school, junior high school, and general high school. We also coded

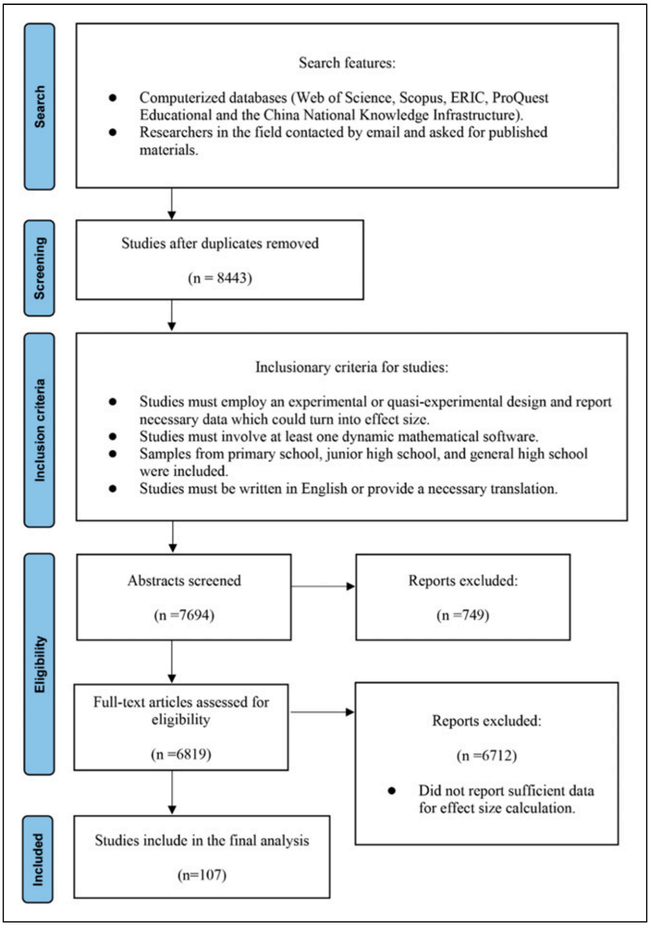

Figure 1. Flow diagram for search and inclusion on studies.

participants' cultural background as a moderator variable according to their country or region reported in the study.

Characteristics of Interventions and Outcomes. The second group of moderators highlighted the differences in pedagogical design. We coded the type of DMS according to the primary study. We categorized users of DMS into teacher, student, and both. As for intervention duration, we categorized it into less than 4 weeks or more than 4 weeks, based on our reading of the included studies and the classification method of the relevant meta-analysis research (Juandi et al., 2021). Besides, we coded the transfer test into far-transfer and near-transfer, referring to the similarity between the test content in the post-test and the domain students learned from DMS. If the post-test was not focused on the knowledge studied based on DMS, we coded it into far-transfer. Otherwise, we coded it into near-transfer.

Statistical Analysis

The metafor package for R statistical program (Viechtbauer, 2010) was used for this analysis. The effect sizes for all studies were displayed by Cohen's *d* value. We considered three variance components distributed across the model's three levels: sampling variance of the extracted effect sizes at Level 1, variance between effect sizes from the same study at Level 2, and variance between studies at Level 3 (Assink & Wibbelink, 2016).

We used the *Q* test of homogeneity to examine whether the variation in the *d* value between studies was significant (Hedges & Olkin, 2014). We calculated the 95%CI for each overall effect size to provide more information regarding the *d* value. Besides, we also computed the Level 1 variance referring to formula by Cheung (2013) and applied the log-likelihood-ratio test to examine heterogeneity at Level 2 and Level 3. In addition, we tested for significance and computed the distribution of the overall variance.

We also examined moderator variables as potential sources of additional variance in the effect size. We conducted linear models to predict the study's outcome from the categorical moderator variables. Additionally, a multiple moderator model was adopted to scrutinize the unique impact of significant moderators in the univariate analysis. We added all the significant moderators to the model and choose the category with the smallest effect size as the reference category to clarify the effectiveness of different designs distinctly. Similarly, by comparing the β-value with CIs between the subsets of studies and using the *Q* test, we investigated the degree of difference and the variance at Level 2 and Level 3.

Publication Bias

To test for publication bias, we first conducted the Egger-MLMA test (Rodgers & Pustejovsky, 2021) and computed Rosenthal's Fail-Safe N (Rosenthal & DiMatteo, 2001), to test the relationship between the size of effects from each study and the associated standard error (Ludwig et al., 2019). We also created funnel plots to test for publication bias (Borenstein et al., 2009). In the funnel plot, the standard error was plotted on the *y*-axis, and the effect size on the *x*-axis. In the absence of retrieval bias, this plot should form an inverted funnel (Georgiou et al., 2023).

Results

Study Features

In general, 107 studies were included in the analysis that consisted of 10,507 students spanning urban and rural schools from the countries such as China, Czech, South

Africa, and America. Of the 107 studies, 22 reported results about more than one effect size. There were 23 studies which published in peer-reviewed journals, 9 proceeding papers and 75 dissertations. The 138 effect sizes ranged from $d = -.665$ to $d = 2.6531$, representing the minimum and maximum effect sizes respectively. 97.1% of effect sizes showed positive, whereas 2.9% of studies showed negative effect sizes, revealing that DMS adversely affected students' learning performance.

Meta-Analytic Results

The overall mean effect size of DMS on students' performance was significant. The mean effect size was $d = .632$ ($p < .001$, 95% CI = [.550, .713], se = .041), indicating a moderate effect. The test for heterogeneity indicated that the effect sizes varied significantly with Q (137) = 544.967, $p < .001$. Furthermore, the log-likelihood-ratio test showed significant heterogeneity at the within-study variance ($p < .05$, Level 2) and the between-study variance ($p < .01$, Level 3). Exactly 22.55% of the total variance could be attributed to Level 1 variance, 18.42% of that could be attributed to the differences at Level 2, and 59.03% could be attributed to Level 3 variance.

Results of the Moderator Analysis

First, we examined if participant characteristics moderated the effect size. As outlined in Table 1, all effect sizes were statistically significant, and cultural background significantly explained the variability in the effect sizes between studies. Although averaged effect sizes for primary school were larger than averaged effect sizes for elder students, the moderation tests showed no statistical significance. What's more, using DMS in counties from East Asia cultural circle yielded smaller effect sizes than using it in other cultural background countries.

The second research question focused on the characteristics of interventions and outcomes, such as which measure is more or less favorable relative to students' performance. The results are presented in Table 2. Studies that did not report on the respective variable were excluded from the moderator analyses. Considering different types of DMS, the effect sizes were stable. Besides, the user of DMS, intervention duration, and degrees of performance transfer were all significant moderators. DMS used by students produced significantly larger effect sizes. Longer intervention duration was less effective than shorter duration. In addition, studies tested near-transfer problems were more effective than studies test far-transfer problems.

It has previously been observed that moderators might be interrelated (Hox et al., 2017). Consequently, significant moderators were added to the multiple moderator model to examine what effects were relevant. As seen in Table 3, the omnibus test showed significant results, F (5,113) = 6.495, $p < .001$. Results indicated that at least one of the regression coefficients of the moderators significantly deviated from zero. According to the findings, we were able to assert that the cultural background and the transfer test were not confounded by the user of DMS and intervention duration. These

Table 1. Summary of the Meta-Analysis Results by Participant Characteristics.

Moderator Variable	*k*	*m*	*n*	*d* (95% CI)	β (95% CI)	F (df1, df2)	*p*-Value	Level 2 Variance	Level 3 Variance
a. School level									
General high school	78	60	59	.602*** (.492, .712)		F (2, 135) = .520	.596	.037*	.111**
Junior high school	48	41	39	.649*** (.512, .787)	.047 (−.129, .224)				
Primary school	12	10	9	.751*** (.467, 1.034)	.149 (−.155, .453)				
b. Cultural background									
East asia cultural circle	98	79	75	.511*** (.423, .600)		F (1, 136) = 24.874	<.001***	.025*	.093**
Others	40	32	32	.939*** (.795, 1.084)	.428*** (.258, .598)				

Note. *k* = numbers of effect sizes; *m* = numbers of samples; *n* = numbers of studies; β = estimated regression coefficient; Level 2 variance = variance between effect sizes extracted from the same study; Level 3 variance = variance between studies; *$p < .05$; **$p < .01$; ***$p < .001$.

Table 2. Summary of the Meta-Analysis Results by Characteristics of Interventions and Outcomes.

Moderator variable	*k*	*m*	*n*	*d* (95% CI)	β (95% CI)	F (df1, df2)	*p*-Value	Level 2 Variance	Level 3 Variance
c. Type of DMS									
GeoGebra	75	60	57	.738*** (.626, .850)		F (7, 130) = 1.337	.238	.033*	.112**
The Geometer's sketchpad	34	23	22	.487*** (.310, .663)	−.252* (−.461, −.042)				
Z + Z super sketchpad	9	8	8	.518*** (.221, .816)	−.220 (.538, .098)				
Hawgent	6	6	6	.420* (.074, .767)	−.318 (−.682, .047)				
Linglong sketchpad	6	6	6	.563** (.217, .910)	−.175 (−.538, .189)				
Cabri 3D	3	3	3	.785** (.265, 1.305)	.047 (−.485, .579)				
Autograph	1	1	1	.734 (−.135, 1.603)	−.004 (−.880, .872)				
Two kinds together	4	4	4	.463* (.037, .889)	−.275 (−.715, .166)				
d. User of DMS									
Teacher	67	54	52	.579*** (.468, .689)		F (2, 124) = 3.605	.030*	.030*	.098**
Student	19	17	17	.881*** (.672, 1.089)	.302* (.066, .538)				
Both	41	34	33	.567*** (.429, .706)	−.011 (−.187, .165)				
e. Intervention duration									
>4 weeks	80	60	58	.519*** (.430, .607)		F (1, 123) = 4.031	.047*	.024*	.060**
≤4 weeks	45	40	38	.665*** (.551, .779)	.146* (.002, .290)				
f. Transfer test									
Near-transfer	107	90	87	.698*** (.606, .789)		F (1,136) = 10.699	.001**	.015*	.133**
Far-transfer	31	27	27	.417*** (.261, .572)	−.281** (−.451, −.111)				

Note. k = numbers of effect sizes; m = numbers of samples; n = numbers of studies; β = estimated regression coefficient; Level 2 variance = variance between effect sizes extracted from the same study; Level 3 variance = variance between studies; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

results suggested that the two moderators had a uniquely moderating effect on the effect.

Publication Bias

The results of the Egger-MLMA test suggested that publication bias should be ignored in our three-level meta-analysis, because the *p*-value of this test exceeded .05. The results of the Fail-Safe N analysis also suggested that estimated effect sizes were reasonably stable. More than 50,000 additional studies would be needed to achieve a null *p*-value. The limit of 5k + 10 studies suggested by Rosenthal (1979), which is 545 in the present analysis, was therefore far exceeded. Subsequently, the symmetric distribution of the funnel plot was depicted in Figure 2, which also indicated that the results of our meta-analysis were stable and reliable.

Discussion

The purpose of this meta-analysis was to calculate the effect size of DMS on students' performance and to clarify what factors moderated this effectiveness. Overall, the analysis added to the field of information and communications technology by confirming a positive medium effect of DMS on enhancing students' abilities (the average effect size was .632). The effect size performed was larger than the results in previous meta-analyses about general educational technology (d = .23, Ran et al., 2022), reflecting the unique advantages of DMS. DMS could create an interactive environment for students to effectively learn through its openness and flexibility. The somewhat smaller over effect size in comparison to the prior meta-analysis about DMS like Chan

Table 3. Multiple Moderator Model.

Moderator Variable		*k*	β (95% CI)
	Intercept		.378*** (.229, .528)
a. Cultural background	Others	21	.332** (.127, .538)
b. User of DMS	Student	15	.069 (−.183, .320)
	Teacher	63	−.052 (−.193, .090)
c. Intervention duration	≤4 weeks	40	.101 (−.047, .250)
d. Transfer test	Near-transfer	91	.168* (.009, .327)
Multiple moderator model	*k* = 119; F (5, 113) = 6.495; *p* < .001***	Level 2 variance .012*	Level 3 variance .052**

Note. *k* = numbers of effect sizes; β = estimated regression coefficient; Level 2 variance = variance between effect sizes extracted from the same study; Level 3 variance = variance between studies; *p < .05; **p < .01; ***p < .001.

and Leung (2014) with $d = 1.02$ and Juandi et al. (2021) with $d = .96$ could result from a broader range of applications in recent years, indicating the left room for go further.

Same as previous viewpoints about representational choices (Acevedo Nistal et al., 2009), this effect was significantly influenced by some of the characteristics of interventions and outcomes, and participant characteristics. Concretely speaking, students would perform better on near-transfer tests, and students from non-East Asia cultural circle showed the strongest effect. Although the user of DMS and intervention duration had significance, the results of the multiple moderator model showed that they were not as steady as thought.

General Applicability of Dynamic Mathematical Software

The study indicated that use DMS by students yielded a larger effect. However, its moderating effects were not robust after controlling for other factors. The better performance outcomes might have been due to more opportunities to engage in hands-on learning and interactive activities (Waight & Gillmeister, 2014). According to Bokosmaty et al. (2017), making manipulations through students' mouse movements would be superior to observing manipulations by teachers with DMS. Moreover, the representation was considered a social activity based on the representative theory. When students were asked to represent data, their outcomes would be a vehicle to discuss and build an active relationship. However, once teachers took sole responsibility, great care would be taken to avoid mistakes in its operation, which reduced the likelihood that students might exhibit (wrong) representations of emergence (Ruthven et al., 2008).

The study has also provided additional evidence concerning the intervention duration. The results showed a bright prospect that DMS had the potential to integrate into normalized teaching practice. There was a significant difference in using time (Chan & Leung, 2014), which showed consistency with earlier research (Juandi et al., 2021). However, after examining all the significant moderators in the multiple moderator model, the difference indicated no significance. Fostering and developing students' representational flexibility was a long process. DMS might play a role in systematically building up new skills over long periods. Taken together, the question is no longer whether we should use DMS or not, but how to use it more effectively in daily education.

Suggestions on Using Dynamic Mathematical Software

Regarding cultural background, we found that students from all over the world were positively improved by using DMS. Furthermore, students from non-East Asia cultural circle showed greater effectiveness. As the theory mentioned earlier, we infer that it is related to students' socio-cultural context and their prior knowledge. Take the representation of problem types in textbooks, the Chinese series paid attention to how the curriculum could establish representations in ways that facilitated the transition process

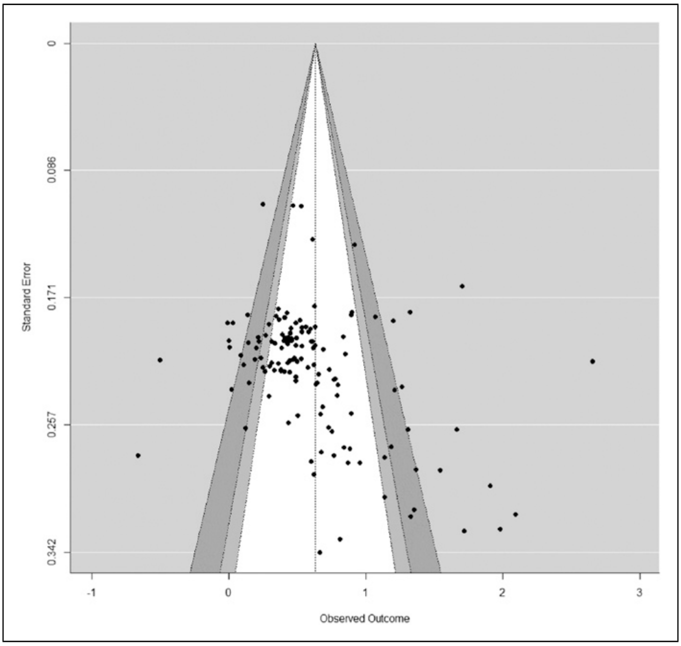

Figure 2. Funnel Plot for all studies.

from concrete to abstract, while textbooks from America and England focused more on openness such as real-life situation word problems. According to the theory of representational flexibility, for students in other cultural circles, DMS could bridge the gap between representations to open problems. This might be an important reason for the significant differences. Multiple moderator model analyses also proved it. Taken together, we urge teachers to plan the use of DMS based on students' characteristics, preparing representational activities, and evaluation or discussion activities to improve students' performance.

We also found that using DMS had a positive impact on both transfer tests. Furthermore, near-transfer tests showed larger effects. The results of the multiple moderator model also indicated the same results. These findings implied that applying DMS in class could lead to transferable skills and competencies, and the results showed that teachers should focus more on creating a proper environment to promote far-transferring performance. Based on the Cognitive Flexibility Theory (Spiro et al., 1992), cognitive and instructional ignorance of problems related to irregular patterns of knowledge use led to students' inability to transfer knowledge. Computers were ideally suited by virtue of the flexibility they could provide for fostering cognitive flexibility (Jacobson & Spiro, 1995). We recommend teachers design more diverse strategies for students to learn, and focus more on students' key competencies rather than knowledge itself. To this day, the idea of interdisciplinary has come a long way, far-transfer and application ability of students are desperately needed in the new educational forms such as STEM and project-based learning. DMS has the potential to serve as an effective approach to supporting these topics (Ziatdinov & Valles, 2022). Further empirical studies are therefore warranted to examine the effects of DMS on students' far-transfer performance.

Conclusion

In conclusion, the present three-level meta-analysis aimed to quantitatively synthesize the overall effect size of DMS. This analysis therefore offers insights into DMS in several ways. Our findings indicate that DMS is an effective technology for improving student performance, suggesting that there is a significant benefit if we properly use DMS in education practice. We also examined the impact of several moderators, and these results have direct implications for instruction and interventions in designing teaching plans. A crucial aspect is the provision of diverse and targeted learning resources that consider the core competencies or key skills they should possess, promoting the outcomes in class effectively transferred to other scenarios. Furthermore, it is essential to plan and execute the time and use of DMS rationally. Let students use the DMS to produce effects that are stronger than letting the teacher control the software. In addition, teachers are encouraged to establish and sustain dynamic interactive environments during teaching, facilitating active student engagement in hands-on activities and enabling them to harness fully the benefits offered by DMS. However, this meta-analysis also underscores areas for future research, including specific populations (e.g., students with learning difficulties).

In spite of these advantages, our study has some limitations. First, it does not account for the moderating effects of participant characteristics such as gender. The reason for this circumstance is that primary studies rarely report on this information. Besides, we acknowledge that some of the categories in the moderator analysis did not include many studies. For instance, when examining the role of type of DMS, we had only three studies that used Cabri 3D, and one study used Autograph. This may have influenced the standard error. Finally, although funnel plot analysis, Egger-MLMA test, and Rosenthal's fail-safe number confirmed that publication bias was not a major problem and we searched for unpublished papers, there might still exist a bias toward significant effects due to the loss of paper which reported non-significant results.

Acknowledgements

The authors thank Huanzhu Liu, Haobo Hu and Weixuan Zhou for their assistance in coding data.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: The authors declare that the research was conducted

in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was partly funded by the National Social Science Fund of China (CHA230308) to Dr Shuang Song.

ORCID iDs

Zhongtian Ji https://orcid.org/0009-0006-7753-1426
Kan Guo https://orcid.org/0000-0003-3188-0947

References

*Studies preceded by an asterisk were included in the meta-analysis.

*Abu Bakar, K., Ayub, A. F. M., & Mahmud, R. (2015). Effects of GeoGebra towards students' mathematics performance. In 2015 International Conference on Research and Education in Mathematics (ICREM7), Kuala Lumpur, Malaysia, 25–27 Aug. 2015.

Acevedo Nistal, A., Van Dooren, W., Clarebout, G., Elen, J., & Verschaffel, L. (2009). Conceptualising, investigating and stimulating representational flexibility in mathematical problem solving and learning: A critical review. *ZDM*, *41*(5), 627–636. https://doi.org/10.1007/s11858-009-0189-1

* Adelabu, F. M., Makgato, M., & Ramaligela, M. S. (2019). The importance of dynamic geometry computer software on learners' performance in geometry. *Electronic Journal of E-Learning*, *17*(1), 52–63.

Aisah, I., Suyudi, M., Carnia, E., Suhendi, & Supriatna, A. K. (2018). Representation mutations from standard genetic codes. In Indonesian Operations Research Association - International Conference on Operations Research 2017, Tangerang Selatan, Indonesia, 12 October 2017.

Aksu, N., & Zengin, Y. (2022). Disclosure of students' mathematical reasoning through collaborative technology-enhanced learning environment. *Education and Information Technologies*, *27*(2), 1609–1634. https://doi.org/10.1007/s10639-021-10686-x

Albaladejo, I. M. R., García, M. d. M., & Codina, A. (2015). Developing mathematical competencies in secondary students by introducing dynamic geometry systems in the classroom. *TED EĞİTİM VE BİLİM*, *40*(177), 43–58. https://doi.org/10.15390/EB.2015.2640

Albano, G., & Dello Iacono, U. (2019). GeoGebra in e-learning environments: A possible integration in mathematics and beyond. *Journal of Ambient Intelligence and Humanized Computing*, *10*(11), 4331–4343. https://doi.org/10.1007/s12652-018-1111-x

Assink, M., & Wibbelink, C. J. M. (2016). Fitting three-level meta-analytic models in R: A step-by-step tutorial. *The Quantitative Methods for Psychology*, *12*(3), 154–174. https://doi.org/10.20982/tqmp.12.3.p154

* Bakar, K. A., Ayub, A. F. M., Tarmizi, R. A., & Luan, W. S. (2015). Effect of teaching mathematics using GeoGebra on students' with dissimilar spatial visualisation. In *The 22nd*

national symposium on mathematical Sciences (Vol. 1682). AIP Publishing. https://doi.org/10.1063/1.4932469

Bantchev, B. B. (2010). *A brief tour to dynamic geometry software* (pp. 1–6). CaMSP February 2015 Newsletter.

* Bayaga, A., Mthethwa, M. M., Bosse, M. J., & Williams, D. (2019). Impacts of implementing GeoGebra on eleventh grade student's learning of euclidean geometry. *South African Journal of Higher Education*, *33*(6), 32–54. https://doi.org/10.20853/33-6-2824

* Binti Misrom, N. S., Muhammad, A. S., Abdullah, A. H., Osman, S., Hamzah, M. H., & Fauzan, A. (2020). Enhancing students' higher-order thinking skills (HOTS) through an inductive reasoning strategy using geogebra. *International Journal of Emerging Technologies in Learning*, *15*(03), 156–179. https://doi.org/10.3991/ijet.v15i03.9839

Birgin, O., & Topuz, F. (2021). Effect of the GeoGebra software-supported collaborative learning environment on seventh grade students' geometry achievement, retention and attitudes. *The Journal of Educational Research*, *114*(5), 474–494. https://doi.org/10.1080/00220671.2021.1983505

Bokosmaty, S., Mavilidi, M. F., & Paas, F. (2017). Making versus observing manipulations of geometric properties of triangles to learn geometry using dynamic geometry software. *Computers and Education*, *113*(3), 313–326. https://doi.org/10.1016/j.compedu.2017.06.008

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to meta-analysis*. Wiley.

Cayton, C., Hollebrands, K., Okumus, S., & Boehm, E. (2017). Pivotal teaching moments in technology-intensive secondary geometry classrooms. *Journal of Mathematics Teacher Education*, *20*(1), 75–100. https://doi.org/10.1007/s10857-015-9314-y

Cekmez, E., & Bulbul, B. O. (2018). An example of the use of dynamic mathematics software to create problem-solving environments that serve multiple purposes. *Interactive Learning Environments*, *26*(5), 654–663. https://doi.org/10.1080/10494820.2017.1385029

Chan, K. K., & Leung, S. W. (2014). Dynamic geometry software improves mathematical achievement: Systematic review and meta-analysis. *Journal of Educational Computing Research*, *51*(3), 311–325. https://doi.org/10.2190/EC.51.3.c

Chang, H. Y., Binali, T., Liang, J. C., Chiou, G. L., Cheng, K. H., Lee, S. W. Y., & Tsai, C. C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers and Education*, *191*(11), Article 104641. https://doi.org/10.1016/j.compedu.2022.104641

* Chang, C. Y., & Bhagat, K. K. (2015). Incorporating GeoGebra into geometry learning-A lesson from India. *Eurasia Journal of Mathematics, Science and Technology Education*, *11*(1), 77–86. https://doi.org/10.12973/eurasia.2015.1307a

* Chen, C. (2018). *Liyong GeoGebra fuzhu gaozhong shuxue jiaoxue yanjiu [A research of using GeoGebra to assist high school mathematics teaching]*. Central China Normal University.

* Chen, N. (2019). *Yong dongtai shuxue jishu tixiao shuxue bianshi jiaoxue de shizheng yanjiu - yi chuzhong pingmian jihe wei li [The empirical research on using dynamic mathematics technology to improve the effectiveness of mathematics variable teaching - taking junior high school plane geometry as an example]*. Guangxi Normal University.

* Chen, S. (2020). *Jihe huaban yingyong yu chuzhong shuxue jiaoxue de tansuo [Geometer sketchpad usage and junior high school math teaching]*. Central China Normal University.

Cheung, W. L. (2013). Modeling dependent effect sizes with three-level meta-analyses: A structural equation modeling approach. *Psychological Methods*, *19*(2), 211–229. https://doi.org/10.1037/a0032968

Ciobanu, A., Miron, C., Berlic, C., & Barna, V. (2022). Modelling the oscillatory motion with geogebra software. *Romanian Reports in Physics*, *74*(3), 906.

* Deng, B. (2013). *Chaoji huaban zhong zidong tuili zai shuxue jiaoxue zhong de yingyong [The application of super sketchpad automated reasoning in maths teaching]*. Guangzhou University.

* Deng, Z. (2018). *GeoGebra fuzhu chuzhong shuxue jiaoxue de shijian yanjiu [A practical study or GeoGebra's assistance in mathmatics teaching in junior middle school]*. Hefei Normal University.

* Gan, C. (2020). *Yingyong haojun (Hawgent) dongtai shuxue ruanjian fuzhu liti jihe jiaoxue de shijian yanjiu [Practical research on the application of Hawgent dynamic mathematics software to assist the teaching of solid geometry]*. Guangxi Normal University.

* Gao, J. (2011). *GeoGebra zai nongcun chuzhong shuxue jiaoxue zhong de yingyong yanjiu [The applied research of GeoGebra in mathematics teaching at rural junior middle schools]*. Henan University.

* Gao, Y. (2019). *Jihe huaban zai chuzhong shuxue jiaoxue zhong de yingyong yanjiu [Exploration and application of the geometer's sketchpad in the junior high school mathematics teaching]*. Central China Normal University.

Gao, Y. (2015). *GeoGebra zai xiaoxue shuxue tuxing yu jihe zuozhongxue de jiaoxue shijian yanjiu [Research on GeoGebra's teaching practice of learning from figures and geometry in primary school mathematics]*. Yunnan Normal University.

* Gecu, Z., & Satici, A. F. (2012). The effects of using digital photographs with Geometer's Sketchpad at 4th Grade. *Procedia - Social and Behavioral Sciences*, *46*(1–2), 1956–1960. https://doi.org/10.1016/j.sbspro.2012.05.410

Georgiou, G. K., Guo, K., Naveenkumar, N., Vieira, A. P. A., & Das, J. P. (2020). PASS theory of intelligence and academic achievement: A meta-analytic review. *Intelligence*, *79*(S101), Article 101431. https://doi.org/10.1016/j.intell.2020.101431

Georgiou, G. K., Vieira, A. P. A., Rothou, K. M., Kirby, J. R., Antoniuk, A., Martinez, D., & Guo, K. (2023). A meta-analysis of morphological awareness deficits in developmental dyslexia. *Scientific Studies of Reading*, *27*(3), 253–271. https://doi.org/10.1080/10888438.2022.2155524

Gokce, S., & Guner, P. (2022). Dynamics of GeoGebra ecosystem in mathematics education. *Education and Information Technologies*, *27*(4), 5301–5323. https://doi.org/10.1007/s10639-021-10836-1

Guven, B., & Kosa, T. (2008). The effect of dynamic geometry software on student mathematics teachers' spatial visualization skills. *Turkish Online Journal of Educational Technology*, *7*(4), 100–107.

* Hannafin, R. D., Truxaw, M. P., Vermillion, J. R., & Liu, Y. (2008). Effects of spatial ability and instructional program on geometry achievement. *The Journal of Educational Research*, *101*(3), 148–157. https://doi.org/10.3200/JOER.101.3.148-157

* He, C. (2015). *Jiyu chaoji huaban de shuxing jiehe sixiang peiyang de jiaoxue yanjiu [The teaching research of numeric-ideas based on super sketchpad]*. Yanbian University.

* He, D. (2019). *Yingyong haojun dongtai shuxue ruanjian fuzhu gaozhong liti jihe jiaoxue de yanjiu [Research on applying Hawgent dynamic mathematics software to assist high school stereo geometry teaching]*. Guangxi Normal University.

* He, Y. (2020). *Wangluo huaban zai chuzhong hanshu jiaoxue zhong de yingyong yanjiu [Research on the application of the network sketchpad in junior high school function teaching]*. Guizhou Normal University.

Hedges, L. V., & Olkin, I. (2014). *Statistical method for meta-analysis*. Academic Press.

Hegedus, S. J., & Otalora, Y. (2023). Mathematical strategies and emergence of socially mediated metacognition within a multi-touch Dynamic Geometry Environment. *Educational Studies in Mathematics*, *112*(2), 289–307. https://doi.org/10.1007/s10649-022-10170-4

Hlalele, B. M. (2020). Developing the usage index for teaching with technology: A case study for motheo district, South Africa. *The Journal for Transdisciplinary Research in Southern Africa*, *16*(1), 1–9. https://doi.org/10.4102/td.v16i1.668

* Hong, Y. (2020). *Jiyu GeoGebra de gaozhong weijifen jiaoxue yanjiu [Research on calculus teaching in senior high school based on GeoGebra]*. Jimei University.

* Hox, J. J., Moerbeek, M., & Schoot, R. V. D. (2017). *Multilevel analysis: Techniques and applications*. Routledge.

* Huang, J. (2018a). *Yingyong haojun (Hawgent) dongtai shuxue ruanjian fuzhu zhongxue shuxue jiaoxue shiyan yanjiu - yi jiben chudeng hanshu (I) wei li [Experimental study on teaching of mathematics teaching in middle school with Hawgent dynamic mathematical software - take basic elementary function (I) as an example]*. Guangxi Normal University.

* Huang, J. (2018b). *Yingyong linglong huaban fuzhu chuzhong shuxue ketang jiaoxue de yanjiu - yi erci hanshu jiaoxue wei li [A research on the application of linglong sketchpad on auxiliary as an auxiliary equipment in middle school's math teaching - a case study of quadratic function teaching]*. Guangxi normal university.

* Huang, X. (2018c). *Yingyong linglong huaban fuzhu xiaoxue tuxing yu jihe de jiaoxue yanjiu [Research on teaching of graphics and geometry in primary school with linglong sketchpad]*. Guangxi Normal University.

* Huang, Z. (2018d). *GeoGebra huanjing xia shuxue keshihua jiaoxue tanjiu - yi yuanzhui quxian yu fangcheng wei li [Exploration of mathematical visualization teaching in GeoGebra environment - taking conic curves and equations as examples]*. Jiangxi Normal University.

* Huang, Y. (2020). *Jiyu GeoGebra de liti jihe jiaoxue yanjiu [A study on the teaching of stereo geometry based on GeoGebra]*. Hunan University of Science and Technology.

Jacobson, M. J., & Spiro, R. J. (1995). Hypertext learning environments, cognitive flexibility, and the transfer of complex knowledge: An empirical investigation. *Journal of Educational Computing Research*, *12*(4), 301–333. https://doi.org/10.2190/4t1b-hbp0-3f7e-j4pn

Jancheski, M. (2019). Educational software for students from kindergartens and lower primary schools. In *INTED2019 Proceedings* (pp. 7603–7612). IATED. https://doi.org/10.21125/inted.2019.1864

* Jelatu, S., Sariyasa, S., & Ardana, I. M. (2018). Effect of GeoGebra-aided REACT strategy on understanding of geometry concepts. *International Journal of Instruction*, *11*(4), 325–336. https://doi.org/10.12973/iji.2018.11421a

Ji, Z. T., & Guo, K. (2023). The association between working memory and mathematical problem solving: A three-level meta-analysis. *Frontiers in Psychology*, *14*, Article 1091126. https://doi.org/10.3389/fpsyg.2023.1091126

* Jin, S. (2017). *Yingyong linglong huaban fuzhu zhongxue shuxue jiaoxue de yanjiu - yi hanshu y=Asin(ωx+φ) de tuxiang jiaoxue wei li [Research on mathematics teaching in middle school with linglong sketchpad - take function y=Asin(ωx+φ) teaching as an example]*. Guangxi Normal University.

* Jiu, X. (2019). *GeoGebra fuzhu zhongxue hanshu jiaoxue de shijian yanjiu [A practical study on GeoGebra aided function teaching in middle school]*. Luoyang Normal University.

* Johari, N. A. i., Chan, L. O., Ramli, R., & Ahmat, N. (2010). The effect of GSP on students' understanding in the graphs of trigonometric functions. In *Fifteenth Asian technology conference in mathematics* (pp. 17–21). ATCM).

Juandi, D., Kusumah, Y. S., Tamur, M., Perbowo, K. S., & Wijaya, T. T. (2021). A meta-analysis of geogebra software decade of assisted mathematics learning: What to learn and where to go? *Heliyon*, *7*(5), Article e06953. https://doi.org/10.1016/j.heliyon.2021.e06953

* Kariadinata, R., Yaniawati, R. P., Juariah, J., Sugilar, H., & Muthmainah, A. (2019). Spatial thinking ability and mathematical character students through Cabri 3D with a scientific approach. *Journal of Physics: Conference Series*, *1402*(7), Article 077094. https://doi.org/10.1088/1742-6596/1402/7/077094

* Kushwaha, R. C., Chaurasia, P. K., & Singhal, A. (2014). Impact on students' achievement in teaching mathematics using geogebra. In 2014 IEEE Sixth International Conference on Technology for Education, Amritapuri, India, 18–21 Dec. 2014. https://doi.org/10.1109/t4e.2014.54

* Kusumah, Y. S., Kustiawati, D., & Herman, T. (2020). The effect of GeoGebra in three-dimensional geometry learning on students' mathematical communication ability. *International Journal of Instruction*, *13*(2), 895–908. https://doi.org/10.29333/iji.2020.13260a

* Lan, J. (2018). *Jiyu jihe huaban de chuzhong shuxue danyuan jiaoxue sheji - yi tuxing de pingyi he xuanzhuan wei li [Unit teaching design of mathematics in junior middle school based on geometer's sketchpad - take the translation and rotation of graphics as an example]*. Ningxia University.

* Lei, X. (2014). *Jihe huaban zai gaozhong shuxue shiyan jiaoxue zhong de yingyong tansuo [The exploration in the geometry sketchpad applied to senior math experiment teaching]*. Central China Normal University.

* Li, D. (2015a). *GeoGebra ruanjian fuzhu shuxue gainian lijiexing xuexi de yanjiu [The research of comprehensible studying for mathematical concepts by the software Geogebra aided instruction]*. Fujian Normal University.

* Li, L. (2015b). *GeoGebra zai chuzhong dongtai jihe jiaoxue zhong de yingyong yanjiu [Research on the application of GeoGebra in dynamic geometry teaching in junior high school]*. Yunnan Normal University.

* Li, Y. (2018). *Jiyu GeoGebra de chuzhong hanshu jiaoxue shijian tanjiu [Exploration of middle school function teaching practice based on GeoGebra]*. Shanghai Normal University.

* Li, X. (2019). *GeoGebra zai chuzhong tuxing yu jihe jiaoxue zhong de yingyong yanjiu [Research on the application of GeoGebra in junior high school graphics and geometry teaching]*. Shandong Normal University.

* Li, Q. (2020a). *GeoGebra fuzhu chuzhong jihe jiaoxue de jiaoxue sheji ji yingyong yanjiu - yi yinchuanshi N zhongxue wei li [Research on teaching design and application of GeoGebra assisted geometric teaching in junior high school - a case study of N high school in Yinchuan]*. Ningxia University.

* Li, Q. (2020b). *Yingyong dongtai shuxue jishu jiejue chuzhong pingmian jihe kaifangti de jiaoxue yanjiu [The application of dynamic mathematics technology to solve open-ended problem of plane geometry in junior high school*. Guangxi Normal University.

Li, Q., & Ma, X. (2010). A meta-analysis of the effects of computer technology on school students' mathematics learning. *Educational Psychology Review*, *22*(3), 215–243. https://doi.org/10.1007/s10648-010-9125-8

* Liang, J. (2017). *Yingyong jihe huaban kaizhan gaosan wenkeban shuxue shiyan de jiaoxue yanjiu [Mathematics experiment with geometer's sketchpad for mathematics teaching of senior three art's students]*. Guangxi Normal University.

* Liang, C. (2019). *GeoGebra zai xiaoxue shuxue tuxing yu jihe jiaoxue zhong de yingyong yanjiu [Application of GeoGebra in primary school mathematical graphics and geometry teaching]*. Guangxi Normal University.

* Liu, D. (2011). *Jihe huaban zai gaozhong shuxue xinkegai zhong dui xuesheng shuxue siwei nengli de peiyang yanjiu [The research of the geometer's sketchpad on the cultivation of students' mathematical thinking ability in the new curriculum reform of high school mathematics]*. Yunnan Normal University.

* Liu, H. (2014a). *Yunyong GeoGebra ruanjian fuzhu chuzhong shuxue jiaoxue xiaoguo yanjiu [Study on teaching effects of GeoGebra in middle school mathematics teaching]*. Nanchang University.

* Liu, Q. (2014b). *GeoGebra fuzhu gaozhong hanshu jiaoxue de yanjiu yu shijian [A study and practice on high school function teaching with GeoGebra]*. Guangxi Normal University.

* Liu, M. (2019). *Jiyu jihe huaban kaizhan chuzhong shuxue shiyan de jiaoxue yanjiu [The teaching research of junior middle school mathematics experiment with geometric sketchpad]*. Shanxi Normal University.

* Liu, L. (2020). *Xinxi jishu zhichi xia de gaozhong jiexi jihe tanjiushi jiaoxue moshi yanjiu [Research on high school analytical geometry inquiry teaching mode supported by information technology]*. Liaoning Normal University.

* Liu, T. (2020). *GeoGebra zai gaozhong sanjiao hanshu jiaoxue zhong de shijian yu yanjiu [The practice and research of GeoGebra in high school trigonometric functions teaching]*. Jiangxi Science and Technology Normal University.

Ludwig, C., Guo, K., & Georgiou, G. K. (2019). Are reading interventions for English language learners effective? A meta-analysis. *Journal of Learning Disabilities*, *52*(3), 220–231. https://doi.org/10.1177/0022219419825855

* Lv, T. (2019). *GeoGebra de shiyong dui hanshu tuxiang bianhuan xuexi de yingxiang - yi hanshu y=Asin(ωx+φ) de tuxiang wei li [Effects of the use of GeoGebra on the learning of functional image transformations - with the image of function y=Asin(ωx+φ) as an example]*. Tianjin Normal University.
* Manganyana, C., van Putten, S., & Rauscher, W. (2020). The use of GeoGebra in disadvantaged rural geometry classrooms. *International Journal of Emerging Technologies in Learning*, *15*(14), 97–108. https://doi.org/10.3991/ijet.v15i14.13739
* Miao, X. (2020). *Renzhi fuhe shijiao xia GeoGebra ruanjian zai shuxue jiaoxue zhong de shijian yanjiu - yi sanjiao hanshu de youdao gongshi jiaoxue wei li [The practical research of GeoGebra software in mathematics teaching from the perspective of cognitive load - taking the teaching of induction formula of trigonometric functions as an example]*. Tianjin Normal University.
* Mthethwa, M., Bayaga, A., Bosse, M. J., & Williams, D. (2020). GeoGebra for learning and teaching: A parallel investigation. *South African Journal of Education*, *40*(2), 1–12. https://doi.org/10.15700/saje.v40n2a1669
* Mu, X. (2018). *Jiyu GeoGebra ruanjian de chuzhong shuxue ketang jiaoxue yanjiu [Study on mathematics teaching in junior middle school based on GeoGebra software]*. Ludong University.
* Munandar, Usman, & Saminan (2020). Analisys of the impact of mathematical learning with geogebra asistance on critical thinking ability. *Journal of Physics: Conference Series*, *1462*(1), Article 012033. https://doi.org/10.1088/1742-6596/1462/1/012033
* Murni, V., Sariyasa, S., & Ardana, I. M. (2017). GeoGebra assist discovery learning model for problem solving ability and attitude toward mathematics. In *Journal of physics: Conference series* (Vol. 895, pp. 012049). IOP Publishing. https://doi.org/10.1088/1742-6596/895/1/012049
* Mushipe, M., & Ogbonnaya, U. I. (2019). Geogebra and grade 9 learners' achievement in linear functions. *International Journal of Emerging Technologies in Learning*, *14*(08), 206–219. https://doi.org/10.3991/ijet.v14i08.9581
* Nocar, D., & Zdrahal, T. (2016). ICT tools used in teaching and learning concept of function in school mathematics. In *ICERI2016 Proceedings* (pp. 11–16). IATED. https://doi.org/10.21125/iceri.2016.1003

Nordin, N., Zakaria, E., Mohamed, N. R. N., & Embi, M. A. (2010). Pedagogical usability of the geometer's sketchpad (GSP) digital module in the mathematics teaching. *Turkish Online Journal of Educational Technology*, *9*(4), 113–117.

* Nurjanah, Latif, B., Yuliardi, R., & Tamur, M. (2020). Computer-assisted learning using the Cabri 3D for improving spatial ability and self- regulated learning. *Heliyon*, *6*(11), Article e05536. https://doi.org/10.1016/j.heliyon.2020.e05536
* Pachemska, S., Atanasova-Pachemska, T., Iliev, D., & Seweryn-Kuzmanovska, M. (2014). Analyses of student's achievement depending on math teaching methods. *Procedia - Social and Behavioral Sciences*, *116*, 4035–4039. https://doi.org/10.1016/j.sbspro.2014.01.886
* Pan, N. (2020). *GeoGebra peiyang xiaoxuesheng shuxue kongjian guannian de shiyan yanjiu [Experimental study on GeoGebra Cultivation of mathematics space concept of primary school students]*. Jiangsu University.

Pankova, E., & Hanc, J. (2019). Flipped learning and interactive methods with smartphones in modern physics at secondary schools. *DIDFYZ 2019: Formation of the Natural Science Image of the World in the 21st Century*, *2152*(1), Article 030025. https://doi.org/10.1063/1.5124769

* Phonguttha, R., Tayraukham, S., & Nuangchalerm, P. (2009). Comparisons of mathematics achievement, attitude towards mathematics and analytical thinking between using the geometer's sketchpad program as media and conventional learning activities. *Mathematics learning*, *7*(19.083), 407.

* Qi, L. (2017). *Pingmian jihe tanjiuxing xuexi yanjiu - yi ls zhongxue jihe huaban yunyong wei li [Research on inquiry learning of plane geometry - taking the application of the geometer's sketchpad in ls middle school as an example]*. Shanghai Normal University.

* Qin, S. (2015). *Z+Z chaoji huaban zai gaozhong shuxue shiyan jiaoxue zhong de yingyong yanjiu [Research on the application of the Z+Z super sketchpad in mathematics experiment teaching in senior high school]*. Central China Normal University.

* Qiu, Y., & Liu, S. (2017). *GeoGebra ruanjian zai gaozhong hanshu jiaoxue zhong de yingyong yanjiu [The study of the application of Geogebra software in high school function teaching]*. Di 22 Jie Quanguo Xinlixue Xueshu Huiyi - Xinlixue Yu Guomin Xinli Jiankang.

Rahimi, S., Shute, V. J., Fulwider, C., Bainbridge, K., Kuba, R., Yang, X. T., Smith, G., Baker, R. S., & D'Mello, S. K. (2022). Timing of learning supports in educational games can impact students? Outcomes. *Computers and Education*, *190*(1), Article 104600. https://doi.org/10.1016/j.compedu.2022.104600

Ran, H., Kim, N. J., & Secada, W. G. (2022). A meta-analysis on the effects of technology's functions and roles on students' mathematics achievement in K-12 classrooms. *Journal of Computer Assisted Learning*, *38*(1), 258–284. https://doi.org/10.1111/jcal.12611

* Reis, Z. A., & Ozdemir, S. (2010). Using Geogebra as an information technology tool: Parabola teaching. *Procedia - Social and Behavioral Sciences*, *9*, 565–572. https://doi.org/10.1016/j.sbspro.2010.12.198

Rodgers, M. A., & Pustejovsky, J. E. (2021). Evaluating meta-analytic methods to detect selective reporting in the presence of dependent effect sizes. *Psychological Methods*, *26*(2), 141–160. https://doi.org/10.1037/met0000300

Rosenthal, R. (1979). The file drawer problem and tolerance for NULL results. *Psychological Bulletin*, *86*(3), 638–641. https://doi.org/10.1037/0033-2909.86.3.638

Rosenthal, R., & DiMatteo, M. R. (2001). Meta-analysis: Recent developments in quantitative methods for literature reviews. *Annual Review of Psychology*, *52*(1), 59–82. https://doi.org/10.1146/annurev.psych.52.1.59

Ruthven, K., Hennessy, S., & Deaney, R. (2008). Constructions of dynamic geometry: A study of the interpretative flexibility of educational software in classroom practice. *Computers and Education*, *51*(1), 297–317. https://doi.org/10.1016/j.compedu.2007.05.013

* Saha, R. A., Ayub, A. F. M., & Tarmizi, R. A. (2010). The effects of GeoGebra on mathematics achievement: Enlightening coordinate geometry learning. *Procedia - Social and Behavioral Sciences*, *8*, 686–693. https://doi.org/10.1016/j.sbspro.2010.12.095

Salas-Rueda, R. A. (2021). Students' perceptions of the use of the flipped classroom during the educational process of linear functions (Percepciones de los estudiantes sobre el uso del aula invertida durante el proceso educativo de las funciones lineales). *Culture and Education*, *33*(3), 431–454. https://doi.org/10.1080/11356405.2021.1949109

* Song, K. (2018). *Jiyu GeoGebra de gaozhong shuxue tanjiuxing jiaoxue yanjiu [The research of high school mathematics inquiry teaching based on GeoGebra]*. Central China Normal University.

Spiro, R. J., Feltovich, P. J., Jacobson, M. J., & Coulson, R. L. (1992). Cognitive flexibility, constructivism, and hypertext: Random access instruction for advanced knowledge acquisition in ill-structured domains. *Constructivism in Education*, *31*(5), 24–33. https://doi.org/10.4324/9780203052600-11

Stein, M. K., Grover, B. W., & Henningsen, M. (1996). Building student capacity for mathematical thinking and reasoning: An analysis of mathematical tasks used in reform classrooms. *American Educational Research Journal*, *33*(2), 455–488. https://doi.org/10.3102/00028312033002455

* Supriadi, N., Kusumah, Y. S., Sabandar, J., & Afgani, J. D. (2014). Developing high-order mathematical thinking competency on high school students' through GeoGebra-assisted blended learning. *Mathematical Theory and Modeling*, *4*(6), 57–66.

* Tang, H. (2020). *Jiyu linglong huaban de liti jihe jiaoxue moshi yanjiu [Research on teaching mode of solid geometry with linglong drawing board]*. Yunnan Normal University.

* Tang, X. (2020). *Jiyu GeoGebra de nongcun chuzhong shuxue tanjiushi jiaoxue shijian yanjiu [GeoGebra-based rural junior middle school mathematics inquiry teaching practice research]*. Northwest Normal University.

* Tao, F. (2017). *Jihe huaban zai chuzhong shuxue jihe tuxing jiaoxue zhong de yingyong yanjiu [Geometer's sketchpad in mathematics teaching in junior high school geometic figure]*. Nanchang University.

* Tarmizi, R. A., Ayub, A. F. M., Abu Bakar, K., & Yunus, A. S. M. (2008). Learning mathematics through utilization of technology: Use of autograph technology vs handheld graphing calculator. In *Proceedings of the 7th WSEAS international conference on Education and Educational Technology* (pp. 21–23). WSEAS Press.

* Thohirudin, M., Maryati, T. K., Dwirahayu, G., & Iop. (2017). Visualisation ability of senior high school students with using GeoGebra and transparent mica journal of physics: Conference series, (*Journal of Physics: Conference Series*, *824*(1), Article 012043. https://doi.org/10.1088/1742-6596/824/1/012043

* Ubuz, B., Ustun, I., & Erbas, A. K. (2009). Effect of dynamic geometry environment on immediate and retention level achievements of seventh grade students. *European Journal of Educational Research*, *9*(35), 147–164.

Ulusoy, F., & Turus, I. B. (2022). The mathematical and technological nature of tasks containing the use of dynamic geometry software in middle and secondary school mathematics textbooks. *Education and Information Technologies*, *27*(8), 11089–11113. https://doi.org/10.1007/s10639-022-11070-z

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48. https://doi.org/10.18637/jss.v036.i03

Waight, N., & Gillmeister, K. (2014). Teachers and students' conceptions of computer-based models in the context of high school chemistry: Elicitations at the pre-intervention stage. *Research in Science Education*, *44*(2), 335–361. https://doi.org/10.1007/s11165-013-9385-7

* Wang, G. (2014). *Gansu sheng gaozhong jihe ruanjian fuzhu shuxue jiaoxue xianzhuang diaocha yu shiyan yanjiu[Investigation and experimental research of teaching in Gansu province high school geometry software aided mathematical]*. Northwest Normal University.

* Wang, W. (2015). *Liyong jihe huaban fuzhu gaozhong wuli shiyan jiaoxue de shijian yanjiu [The practice research of using the geometer's sketchpad in the high school physics experiment teaching]*. Ningbo University.

* Wang, Y. (2016). *GeoGebra zai chuzhong shuxue jiaoxue zhong de yingyong yanjiu [Research on the Application of GeoGebra in Middle School Mathematics Teaching]*. Nanchang University.

* Wang, Y. (2017). *Jiyu chaoji huaban de chuzhong tongji yu gailv zhiguanxing jiaoxue shijian yanjiu [Intuitive teaching practice research in statistics and probability of junior high school based on super sketchpad]*. Ludong University.

* Wang, L. (2018). *Linglong huaban fuzhu gaozhong liti jihe jiaoxue de yanjiu [The research on aiding high school geometry teaching with linglong 3D board]*. Guangxi Normal University.

* Wang, S. (2019). *GeoGebra zai gaozhong liti jihe jiaoxue zhong de yingyong yanjiu [Research on the application of GeoGebra in the teaching of solid geometry in senior high school]*. Shandong Normal University.

* Wang, S. (2020a). *Jiyu wangluo huaban de gaozhong shuxing jiehe sixiang jiaoxue yanjiu - yi hanshu wei li [Teaching research on the thought of symbolic-graphic combination in high school based on network sketchpad - taking functions as examples]*. Hainan Normal University.

* Wang, W. (2020b). *Xinxi jishu yu gaozhong hanshu jiaoxue shendu ronghe de celve yanjiu [Research on the strategy of deep integration of information technology and function teaching in senior high school]*. Hunan University of Science and Technology.

* Wei, S. (2018). *Dongtai jihe huanjing xia jiyu fanxier lilun de jihe gainian jiaoxue yanjiu [Research on geometric concept teaching design based on van hiele theory in dynamic geometric environment]*. Liaoning Normal University.

* Wei, C. (2020). *Jiyu GeoGebra fuzhu de gaozhong wuli weike jiaoxue sheji yu shijian [GeoGebra-assisted high school physics microlecture teaching design and practice]*. Shihezi University.

Weng, X. J., Ng, O. L., & Chiu, T. K. F. (2023). Competency development of pre-service teachers during video-based learning: A systematic literature review and meta-analysis. *Computers and Education*, *199*(1), Article 104790. https://doi.org/10.1016/j.compedu.2023.104790

Widodo, S. A., DarhimIkhwanudin, T., & Iop. (2017). Improving mathematical problem solving skills through visual media. In *Journal of Physics: Conference Series* (Vol. 948, pp. 012004). IOP Publishing). https://doi.org/10.1088/1742-6596/948/1/012004

* Xiang, S. (2012). *Jihe huaban yu gaozhong shuxue kecheng zhenghe de yanjiu [The integration of the geometer sketchpad and mathematics curriculum]*. Northeast Normal University.

* Xiao, M. (2020). *Xinxi jishu zhichi xia de HPM jiaoxue shijian yanjiu - yi zugeng yuanli he dandelin shuangqiu moxing wei li [Case study on HPM teaching supported by information technology - taking zugeng's theorem and dandelin spheres as examples]*. Jiangxi Normal University.
* Xie, M. (2019). *Cabri 3D zai gaozhong liti jihe jiaoxue zhong de yingyong yanjiu [The study on application of Cabri 3D in high school solid geometry teaching]*. Hunan Normal University.
* Xu, J. (2019). *Jiyu jihe huaban de gaozhong wuli youxiao jiaoxue tantao - yi bo de yanshe he ganshe wei li [Exploration of effective teaching of high school physics based on geometric sketchpad - take diffraction and interference of waves as an example]*. Gannan Normal University.
* Xu, H. (2020). *Xinxi jishu youhua gaozhong shuxue wenti daoxue jiaoxue de shijian yanjiu - yi hanshu wei li [Practical research on applying information technology to optimize the teaching of mathematics problem guidance in high school - take "function" as an example*. Guangxi Normal University.
* Yan, C. (2018). *Yingyong linglong huaban jijian fuzhu gaozhong shuxue jiaoxue de yanjiu [Application of linglong sketchpad integrable ware to assis senior high school mathematical teaching]*. Guangxi Normal University.
* Yan, X. (2018). *DGS fuzhu xia de chuzhong jihe jiaoxue shijian yanjiu - yi liunianji shuxue wei li [A practical study on junior high school geometry teaching assisted by DGS - taking sixth grade mathematics as an example]*. Shanghai Normal University.
* Yang, S. (2008). *Chaoji huaban yu chuzhong shuxue kecheng zhenghe de jiaoxue yingyong yanjiu [Research of teaching application on integration of super's sketchpad and junior middle school mathematics curriculum]*. Central China Normal University.
* Yang, L. (2012). *Chaoji huaban yu gaozhong hanshu jiaoxue zhenghe de youxiaoxing yanjiu [Effectiveness research on the integration of super sketchpad and function teaching in senior school]*. Hainan Normal University.
* Yang, X. (2018). *Jihe huaban linglong huaban yu Hawgent haojun de bijiao ji zai shuxue jiaoxue zhong de yingyong yanjiu [Comparison and Application Research of Geometric Sketchpad, Linglong sketchpad and Hawkent in mathematics teaching]*. Guangxi Normal University.
* Yang, T. (2019). *Jichu shuxue ruanjian yingyong yu gaozhong shuxue jiaoxue de youshi fenxi yanjiu [Analysis and research on the advantages of the application of mathematical software in high school mathematics teaching]*. Central China Normal University.
* Yin, Y. (2016). *GeoGebra zai gaozhong sanjiao hanshu jiaoxue zhong de yingyong yanjiu [Research on the application of GeoGebra in the teaching of trigonometric functions in senior high school]*. Yunnan Normal University.
* Yu, X. (2015). *Yunyong jihe huaban kaizhan chuzhong shuxue shiyan de jiaoxue yanjiu [Using the geometer's sketchpad to carry out the teaching research of junior high school mathematics experiment]*. Yunnan Normal University.
* Zamri, S. N. A. S., & Zakaria, E. (2017). Conceptual and procedural knowledge: An effectiveness study on GeoGebra software. *Advanced Science Letters*, *23*(3), 2079–2082. https://doi.org/10.1166/asl.2017.8562

* Zengin, Y., Furkan, H., & Kutluca, T. (2012). The effect of dynamic mathematics software geogebra on student achievement in teaching of trigonometry. *Procedia - Social and Behavioral Sciences*, *31*(1), 183–187. https://doi.org/10.1016/j.sbspro.2011.12.038

* Zhang, J. (2008). *Jihe huaban yingyong yu gaozhong shuxue shiyan de jiaoxue yanjiu [The teaching research of the geometers' sketchpad applied in high school mathematics experiment]*. Sichuan Normal University.

* Zhang, M. (2017). *GeoGebra zai xiaoxue shuxue jiaoxue zhong de yingyong yanjiu [Study on application of GeoGebra in primary school mathematics teaching]*. Northwest Normal University.

* Zhang, X. (2020). *Jiyu jihe huaban de chuzhong shuxue jiaoxue shizheng yanjiu [Empirical research on junior middle school mathematics teaching based on geometric sketchpad]*. Tianjin University.

* Zhu, L. (2020). *Jiyu GeoGebra de gaozhong shuxue tanjiushi jiaoxue yanjiu [The research of high school mathematics inquiry teaching based on GeoGebra]*. Shaanxi University of Technology.

Ziatdinov, R., & Valles, J. R. (2022). Synthesis of modeling, visualization, and programming in GeoGebra as an effective approach for teaching and learning STEM topics. *Mathematics*, *10*(3), 398. https://doi.org/10.3390/math10030398

* Zong, L. (2019). *GeoGebra zai qinianji jihe jiaoxue zhong de yingyong yanjiu [A research on the application of GeoGebra to first year junior high school geometry teaching]*. Tianshui Normal University.

* Zulnaidi, H., Oktavika, E., & Hidayat, R. (2020). Effect of use of GeoGebra on achievement of high school mathematics students. *Education and Information Technologies*, *25*(1), 51–72. https://doi.org/10.1007/s10639-019-09899-y

* Zulnaidi, H., & Syed Zamri, S. N. A. (2017). The effectiveness of the GeoGebra software: The intermediary role of procedural knowledge on students' conceptual knowledge and their achievement in mathematics. *Eurasia Journal of Mathematics Science And Technology Education*, *13*(6), 2155–2180. https://doi.org/10.12973/eurasia.2017.01219a

Author Biographies

Zhongtian Ji is a PhD Candidate in Dr Guo's Lab in the School of Mathematical Sciences at Beijing Normal University. Her research interests include mathematics education and educational technology.

Kan Guo is an associate professor in the School of Mathematics Sciences at Beijing Normal University. His research interests are in the aeras of mathematics education, educational technology and educational assessment.

Shuang Song is an associate professor in College of Teacher Education at Capital Normal University. Her research interests are in the aeras of language, child development, and learning disability.