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Digital mind mapping-integrated think-pair-share and cognitive styles in geometry learning: evidence from secondary school students

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Abstract

Background: Integrating digital learning technologies with cooperative learning has become an important strategy for enhancing mathematics instruction. However, empirical evidence regarding the effectiveness of Digital Mind Mapping integrated into the Think-Pair-Share (DMM-TPS) model remains limited, particularly concerning whether its effectiveness varies across students with different cognitive styles.
Aim: This study examined the effectiveness of the DMM-TPS model in improving secondary students' geometry understanding and investigated whether learning outcomes differed between students with visualizer and verbalizer cognitive styles.
Method: A quasi-experimental design was employed involving 60 secondary students, comprising equal numbers of visualizers and verbalizers in the experimental and control groups. Data were collected using a geometry understanding test and a cognitive style questionnaire and analyzed through Two-Way Analysis of Covariance (ANCOVA) with pre-test scores as covariates.
Results: The DMM-TPS model produced a significant improvement in geometry understanding with a moderate effect size ($\eta^2 = 0.10$). Students in the experimental group achieved a meaningful average gain of 4.07 points, reflecting a shift from sufficient to good performance. Neither cognitive style nor its interaction with the learning model significantly affected students' achievement, indicating consistent benefits for both visualizers and verbalizers.
Conclusion: DMM-TPS provides a significant and pedagogically meaningful improvement in geometry understanding regardless of students' cognitive styles. Mathematics instruction should therefore prioritize cooperative learning supported by digital mind mapping rather than differentiating instruction based on cognitive style.

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INTRODUCTION

Mathematics education plays a fundamental role in equipping students with critical thinking, analytical reasoning, and problem-solving competencies that are essential for addressing increasingly complex challenges in the twenty-first century. Among the fundamental topics in secondary mathematics, Systems of Linear Equations in Two Variables (SPLDV) is particularly important because it provides the conceptual foundation for mathematical modeling and supports applications across economics, science, engineering, and everyday decision-making (Tobar et al., 2025). Consequently, students' conceptual understanding of SPLDV is regarded as a prerequisite for mastering more advanced mathematical concepts and developing higher-order mathematical reasoning. Despite its importance, mathematics achievement remains a major educational concern worldwide, particularly in developing countries. The Programme for International Student Assessment (PISA) 2022 reported that Indonesian students obtained an average mathematics score

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of only 366, ranking 70th out of 81 participating countries, which is substantially below the OECD average of 472, while only 18% of Indonesian students achieved at least Level 2 proficiency, compared with the OECD average of 69%. This result also reflects a decline from Indonesia's performance in the previous PISA cycle, indicating that efforts to improve students' mathematical competencies have yet to produce substantial progress. Similar concerns are reflected in Indonesia's Minimum Competency Assessment (AKM), where although the proportion of students achieving minimum numeracy competency increased from 45.24% in 2022 to 67.94% in 2024, nearly one-third of students still failed to meet the expected standard (Prigaswari et al., 2025). These findings indicate that persistent learning difficulties cannot be addressed solely through curriculum improvement but also require instructional approaches capable of promoting meaningful conceptual understanding and accommodating diverse learner characteristics (Prasetya, 2025). Consistent with these national findings, students at MTs Negeri 2 Surabaya have demonstrated relatively low achievement in SPLDV, with many learners consistently failing to attain the school's Minimum Mastery Criteria (KKM), particularly on tasks requiring conceptual reasoning and analytical thinking. Therefore, improving students' understanding of mathematical concepts through more adaptive and student-centered instructional strategies has become an urgent priority for mathematics education research and classroom practice.

Learning effectiveness in mathematics is influenced not only by instructional methods but also by individual cognitive characteristics that determine how students perceive, organize, and process mathematical information. From the perspectives of Dual Coding Theory and Cognitive Load Theory, meaningful learning is facilitated when instructional representations correspond to learners' preferred cognitive processing pathways, thereby minimizing unnecessary cognitive load and promoting the construction of coherent conceptual schemas (Apostolou & Linardatos, 2023; Christ et al., 2026; Nordin et al., 2026; Twabu, 2025). One widely accepted classification distinguishes students into Visualizer and Verbalizer cognitive styles, each demonstrating different preferences in processing and representing information (Arıkan, 2025; Lai et al., 2021; Lin et al., 2024; Melzner & Kappes, 2025; Wu et al., 2026). Visualizers generally comprehend mathematical ideas more effectively through diagrams, images, spatial relationships, and graphical representations, whereas Verbalizers tend to process information more efficiently through written texts, verbal explanations, and sequential descriptions (Handayani & Mulyono, 2025). Nevertheless, conventional mathematics instruction continues to emphasize teacher-centered verbal explanations that frequently overlook these cognitive differences, thereby limiting opportunities for students to construct meaningful conceptual understanding. Such instructional mismatches may increase extraneous cognitive load and reduce students' ability to establish meaningful relationships among mathematical concepts, symbols, and procedures. In response to these challenges, Digital Mind Mapping has emerged as an instructional technology that facilitates the visual organization of knowledge while encouraging students to actively construct conceptual relationships. Previous studies have demonstrated that digital mind mapping enhances memory retention, creativity, conceptual organization, and mathematical concept understanding by enabling learners to connect related ideas in meaningful ways. Furthermore, visually organized learning environments developed through digital mind mapping appear to provide greater benefits for students with Visualizer cognitive styles because graphical representations facilitate conceptual processing and reduce representational complexity (Islami & Triyana, 2024). However, existing evidence also suggests that Verbalizer learners may benefit optimally only when visual learning tools are complemented by structured verbal explanations, implying that the instructional effectiveness of digital mind mapping may vary according to students' cognitive characteristics rather than functioning as a universally effective learning approach.

Beyond selecting appropriate instructional media, meaningful mathematics learning also requires learning environments that actively engage students in constructing knowledge through collaboration, discussion, and shared reasoning. Cooperative learning has consistently been recognized as an effective pedagogical approach because it promotes communication, shared responsibility, and collective problem solving while encouraging students to articulate, evaluate, and refine their mathematical thinking through social interaction. Among various cooperative learning models, Think-Pair-Share (TPS) provides a systematic sequence of individual thinking, peer discussion, and whole-class sharing that encourages active participation and deeper conceptual understanding (Nofitri & Sukma, 2026). The TPS learning model has also been shown to improve students' engagement, mathematical reasoning, communication, and problem-solving performance by providing opportunities to exchange ideas and evaluate alternative solution strategies collaboratively (Jayanti et al., 2023; Trisnadewi et al., 2025). Integrating Digital Mind Mapping into the TPS learning process offers opportunities to strengthen both the visual organization of mathematical concepts and the collaborative construction of knowledge during peer interaction. Through this instructional integration, students are encouraged to externalize their conceptual understanding in visual forms while simultaneously negotiating mathematical meaning through structured collaborative discussion. Such an instructional design is theoretically expected to accommodate both Visualizer and Verbalizer learners by combining graphical representations with verbal interaction during different stages of the learning process. Despite these potential advantages, empirical studies investigating the integration of Digital Mind Mapping within the TPS cooperative learning model remain relatively limited in mathematics education, particularly at the junior secondary level (Anggraini & Abduh, 2022). Moreover, little empirical evidence is available regarding whether the effectiveness of this integrated instructional approach differs according to students' cognitive styles, especially in learning Systems of Linear Equations in Two Variables (SPLDV). Therefore, investigating the effectiveness of Digital Mind Mapping-integrated Think-Pair-Share while considering Visualizer and Verbalizer cognitive styles is expected to provide a more comprehensive understanding of how technology-enhanced cooperative learning can improve students' mathematical concept understanding across diverse learner characteristics.

Although previous studies have consistently demonstrated the educational benefits of digital technologies, collaborative learning, and innovative instructional approaches in mathematics education, several important research gaps remain. Existing studies have shown that digital mind mapping effectively supports knowledge organization, collaborative knowledge construction, and learning achievement, while technology-enhanced collaborative learning environments have been associated with improved mathematical reasoning and student engagement (Y. Shi et al., 2023). Likewise, Think-Pair-Share (TPS) has been widely recognized as an effective cooperative learning strategy for promoting students' mathematical problem-solving and classroom interaction (Alsmadi et al., 2023). In geometry education, recent research has predominantly focused on technology-assisted interventions such as GeoGebra, augmented reality, Moodle-based learning, and other digital environments to improve conceptual understanding and higher-order thinking skills (Gurmu et al., 2024; Jablonski & Ludwig, 2023). However, these research streams have largely been investigated independently, with limited attention given to integrating Digital Mind Mapping within the Think-Pair-Share cooperative learning model in secondary geometry instruction. Furthermore, although individual differences in cognitive style have long been acknowledged as influential factors in mathematics learning, empirical evidence examining whether visualizer and verbalizer cognitive styles moderate the effectiveness of technology-supported cooperative learning remains scarce. Consequently, it is still unclear whether integrating Digital Mind Mapping into Think-Pair-Share produces comparable learning benefits across different cognitive style profiles or whether instructional effectiveness depends on students' representational preferences. Addressing this gap is expected to contribute new empirical evidence regarding the interaction between digital learning technology, cooperative pedagogy, cognitive diversity, and geometry concept understanding in secondary mathematics education.

This study aims to examine the effectiveness of integrating Digital Mind Mapping (DMM) into the Think-Pair-Share (TPS) cooperative learning model in enhancing junior secondary students' mathematical concept understanding of Systems of Linear Equations in Two Variables (SPLDV). Specifically, the study evaluates whether the DMM-TPS learning model produces higher conceptual understanding than conventional instruction after controlling for students' initial mathematical ability. It also investigates whether students with Visualizer and Verbalizer cognitive styles differ significantly in their mathematical concept understanding. In addition, the study explores whether cognitive style moderates the effectiveness of the DMM-TPS learning model on students' conceptual understanding. By examining these relationships simultaneously, this research provides a more comprehensive evaluation of how instructional design and learner characteristics interact in mathematics learning. Unlike previous studies that primarily focused on the independent effects of digital learning tools or cooperative learning strategies, this study integrates both approaches within a single instructional framework while considering cognitive diversity. This integrated perspective is expected to generate empirical evidence regarding the consistency of DMM-TPS effectiveness across different cognitive style profiles. The findings are anticipated to contribute to the growing body of knowledge on technology-enhanced mathematics education by clarifying the pedagogical value of combining visual learning technologies with cooperative learning practices. From a practical perspective, the study is expected to provide evidence-based recommendations for mathematics teachers in designing more adaptive, inclusive, and cognitively responsive learning environments. Ultimately, the research seeks to support the development of instructional practices that improve students' mathematical concept understanding while accommodating individual differences in cognitive processing.

LITERATURE REVIEW

Mathematical concept understanding constitutes a central dimension of mathematics proficiency because it enables students to interpret mathematical ideas, recognize relationships among concepts, select appropriate representations, and apply knowledge across different problem situations. Conceptual understanding differs from procedural competence in that students are expected not merely to execute algorithms but also to explain why mathematical procedures work and how mathematical ideas are interconnected. This distinction is particularly relevant to Systems of Linear Equations in Two Variables (SPLDV), where successful learning requires students to coordinate algebraic expressions, graphical representations, solution procedures, and contextual meanings (Kholifah et al., 2026). Students with insufficient conceptual understanding may be able to perform elimination or substitution mechanically while experiencing difficulty interpreting solutions or translating contextual problems into mathematical models. Such difficulties indicate that mathematics instruction should provide opportunities for students to construct relationships among representations rather than simply reproduce predetermined procedures. Conceptual understanding can be strengthened when learners actively organize prior and new knowledge, articulate mathematical reasoning, and compare alternative representations during learning. In this regard, instructional environments that combine visualization with meaningful interaction may provide stronger support for understanding abstract mathematical relationships. Digital technologies can facilitate this process by allowing mathematical information to be represented, reorganized, and connected in forms that are more accessible to learners (Cirneanu & Moldoveanu, 2024; Weinhandl et al., 2021). Nevertheless, the pedagogical contribution of technology depends on how digital resources are integrated into learning activities rather than on the mere presence of technological devices or applications. Therefore, technology-enhanced mathematics instruction needs to connect digital representation, active knowledge construction, and pedagogically structured interaction to promote meaningful mathematical concept understanding.

Digital Mind Mapping (DMM) represents one technology-supported approach that can assist learners in externalizing and organizing conceptual relationships through interconnected visual structures. Unlike linear note-taking, mind mapping organizes information around central ideas and develops relationships through branches, keywords, symbols, images, and other visual elements, thereby making conceptual connections more explicit (Hazaymeh & Alomery, 2022). Within mathematics learning, this organizational structure can help students identify relationships among definitions, mathematical properties, representations, procedures, and applications rather than treating each component as isolated information. Digital environments further extend conventional mind mapping by enabling learners to revise, rearrange, expand, and connect information dynamically throughout the knowledge-construction process (Elhilal, 2025; Muneer Al Sheikh & Hamza Al Jazzar, 2026; Yang et al., 2025). Previous evidence indicates that mind mapping can support memory, creativity, conceptual organization, and mathematical understanding by facilitating meaningful connections among related ideas (Kefalis et al., 2025; Y. Shi et al., 2023). Its visual characteristics may be particularly relevant to mathematical topics such as SPLDV because students must coordinate symbolic equations, graphical relationships, solution methods, and contextual interpretations within a coherent conceptual structure. Digital mind maps can consequently function not only as presentation media but also as cognitive tools through which students externalize and examine the organization of their mathematical knowledge. This function is consistent with the view that effective digital learning should enable learners to manipulate and reconstruct knowledge rather than passively receive information. However, visually rich instructional tools do not necessarily produce equivalent benefits for every learner because students differ in how they preferentially process and communicate information. Accordingly, the pedagogical potential of DMM needs to be examined alongside instructional strategies that provide opportunities for verbal elaboration and collaborative meaning-making.

Think-Pair-Share (TPS) provides such opportunities through a cooperative structure that systematically combines individual reasoning, peer interaction, and collective communication. The model generally proceeds through three interconnected stages in which students first formulate ideas independently, subsequently discuss their reasoning with a partner, and finally communicate the resulting understanding to a wider learning community (Nofitri & Sukma, 2026). The *think* phase provides learners with sufficient cognitive space to activate prior knowledge and formulate an initial response before being influenced by other students' ideas. During the *pair* phase, students articulate their reasoning, identify differences between solution strategies, negotiate meaning, and revise misconceptions through reciprocal explanation. The *share* phase subsequently extends these interactions by exposing students to alternative representations and mathematical arguments within the classroom community. Such structured interaction can strengthen engagement, mathematical reasoning, and problem-solving performance because learners are required to explain and evaluate mathematical ideas rather than simply report final answers (Jayanti et al., 2023; Trisnadewi et al., 2025). Cooperative learning more broadly also facilitates shared responsibility and conceptual development through social interaction among learners. When DMM is incorporated into TPS, the mind map can serve as a representational artifact through which individually generated ideas are visually organized, discussed with peers, and refined during classroom sharing. This integration therefore establishes complementary learning processes in which DMM supports the organization and visualization of knowledge, while TPS provides verbal elaboration, negotiation, and collaborative validation of that knowledge. The combination of these mechanisms provides a theoretical basis for expecting DMM-TPS to promote mathematical concept understanding more effectively than instruction dominated by explanation and routine procedural practice.

The potential effectiveness of DMM-TPS should nevertheless be considered in relation to Visualizer and Verbalizer cognitive styles, as learners may differ in the ways they preferentially receive, organize, and communicate information. Visualizer–Verbalizer distinctions describe tendencies toward processing information predominantly through imagery and spatial representations or through linguistic and verbal forms, respectively. Visualizers commonly favor diagrams, images, graphical patterns, and spatial relationships, whereas Verbalizers tend to rely more strongly on written language, oral explanations, and sequential verbal information (Koć-Januchta et al., 2020; Menendez, 2026; W. Shi et al., 2025). These differences are relevant to mathematics because mathematical meaning is communicated through multiple representational systems, including symbolic, graphical, verbal, and numerical forms. From a dual-coding perspective, learning can be strengthened when verbal and non-verbal representational systems are meaningfully coordinated rather than treated as competing channels. Cognitive load principles similarly suggest that the design and presentation of information can influence the mental resources available for constructing and integrating mathematical schemas. Digital mind mapping may initially appear particularly compatible with Visualizers because its graphical organization makes relationships among concepts spatially explicit, and previous research has suggested benefits of visually structured learning for these learners (Islami & Triyana, 2024). TPS, in contrast, provides substantial opportunities for verbal articulation and interpersonal explanation, which may support Verbalizers while simultaneously requiring Visualizers to translate visualized ideas into communicable mathematical reasoning. Integrating the two approaches may therefore create a multimodal instructional environment in which neither visual nor verbal processing is exclusively privileged. Rather than assuming that one cognitive style inherently produces superior mathematics achievement, examining Visualizer–Verbalizer differences within DMM-TPS can reveal whether an integrated visual-cooperative environment provides consistent benefits across heterogeneous learners.

The theoretical relationship among DMM, TPS, cognitive style, and mathematical concept understanding suggests that instructional effectiveness may emerge from the coordination of visual organization, individual reasoning, and collaborative verbal elaboration rather than from any component operating independently. In the proposed framework, DMM provides an external visual structure for organizing mathematical relationships, while TPS creates a social mechanism through which these representations can be explained, challenged, and reconstructed (Li et al., 2025). Visualizer and Verbalizer cognitive styles represent learner characteristics that may potentially influence how effectively students engage with these visual and verbal components of instruction. Consequently, cognitive style can be examined not simply as a basis for classifying students but as a potential moderating factor in determining whether the effect of DMM-TPS on conceptual understanding varies across learners. This perspective is particularly important because designing separate instructional pathways for different cognitive styles would have substantial pedagogical implications if meaningful interaction effects were demonstrated. Conversely, a non-significant interaction would indicate that a sufficiently multimodal instructional design may function consistently across cognitive preferences, reducing the pedagogical necessity of separating learners according to Visualizer–Verbalizer classifications. Such an interpretation shifts attention from matching instruction rigidly to presumed learning preferences toward designing learning environments that offer complementary representational and communicative opportunities. In SPLDV learning, this integration can allow students to visually organize equations and their relationships, independently develop solution reasoning, discuss interpretations with peers, and communicate conceptual connections across representations. Examining both the main effect of

DMM-TPS and its interaction with cognitive style therefore provides a stronger empirical basis for determining whether improved mathematical understanding originates primarily from instructional design, learner characteristics, or their interaction. Taken together, this framework positions DMM-TPS as a technology-enhanced cooperative approach whose effectiveness can be evaluated not only through overall learning gains but also through its capacity to support mathematical concept understanding consistently among students with different cognitive processing preferences.

METHOD

Research Design

This study employed a quantitative approach with a quasi-experimental design, specifically a nonequivalent control group design, to examine the effectiveness of Digital Mind Mapping integrated with the Think-Pair-Share cooperative learning model (DMM-TPS) in improving students' mathematical concept understanding. The quasi-experimental approach was selected because the participants were organized within existing classes, making individual random assignment impractical in the natural school setting. Two intact classes were designated as the experimental and control groups while maintaining their established classroom composition. The experimental group received Digital Mind Mapping-integrated Think-Pair-Share (DMM-TPS) instruction, whereas the control group received conventional TPS instruction without Digital Mind Mapping. This comparison was intended to isolate the contribution of Digital Mind Mapping when embedded within the same cooperative learning structure rather than comparing DMM-TPS with an entirely different pedagogical model. Both groups completed a pre-test before the intervention and a post-test following the instructional period to measure changes in mathematical concept understanding. In addition to the instructional condition, students were classified according to Visualizer and Verbalizer cognitive styles. The design therefore incorporated two categorical factors, namely learning model and cognitive style, while students' initial mathematical understanding was statistically controlled through their pre-test scores. This structure enabled simultaneous examination of the main effect of the learning model, the main effect of cognitive style, and the interaction between the two factors. Accordingly, the design provided an appropriate framework for determining whether DMM-TPS was effective across cognitive styles or whether its effect on mathematical concept understanding varied between Visualizer and Verbalizer students.

Participant

The population comprised all eighth-grade students at MTs Negeri 2 Surabaya during the 2024/2025 academic year, from which two intact classes were selected through purposive sampling. The sampling procedure considered the suitability of the classes for implementing the intervention while preserving the authentic organization of mathematics instruction at the school. A total of 60 students were included in the final sample, with 30 students assigned to the experimental group and 30 to the control group based on their existing class membership. To maintain a balanced factorial structure, each instructional group consisted of 15 Visualizer and 15 Verbalizer students, resulting in four subgroups with equal sample sizes. Participants were included when they completed the cognitive style questionnaire, could be classified as either Visualizer or Verbalizer, participated in the complete research sequence from pre-test through post-test, and represented heterogeneous levels of initial mathematical ability. Students who did not complete the required research stages were excluded from the final analytical sample to ensure comparability across measurements. Cognitive style classification was conducted before the intervention so that the distribution of Visualizer and Verbalizer students could be identified within each instructional condition. The use of intact classes maintained the ecological characteristics of actual classroom learning, although individual participants were not randomly assigned to treatment conditions. Both groups studied the same mathematical topic, Systems of Linear Equations in Two Variables (SPLDV), during the research period. This participant structure enabled comparisons between instructional conditions and cognitive styles while also allowing their potential interaction to be examined statistically.

Instrument

Four instruments were employed to collect and support the research data: a mathematical concept understanding test, cognitive style questionnaire, teaching module, and classroom documentation sheets. Students' mathematical concept understanding was assessed using pre-test and post-test essay assessments consisting of five questions covering SPLDV, with responses evaluated using a detailed scoring rubric. The assessment was designed to capture conceptual understanding rather than procedural calculation alone by requiring students to interpret, apply, and connect mathematical concepts in solving SPLDV-related problems. The content and suitability of the test were validated by a mathematics expert before its administration to ensure alignment between the items, learning objectives, and targeted mathematical competencies. Students' cognitive styles were identified using a 20-item Likert-scale questionnaire, consisting of 10 statements representing Visualizer characteristics and 10 representing Verbalizer characteristics. Questionnaire scores were interpreted according to Andrew L. Mendelson's scoring rules to classify each participant as either a Visualizer or Verbalizer. The teaching module was developed to standardize the implementation of the instructional stages and ensure that the experimental treatment followed the intended integration of Digital Mind Mapping with TPS. Documentation sheets were additionally used to record classroom activities and provide evidence regarding the fidelity of instructional implementation throughout the intervention. Data collection generated three principal forms of evidence: students' cognitive style classifications, pre-test and post-test mathematical concept understanding scores, and records concerning the implementation of the instructional procedures. Collectively, these instruments enabled the study to evaluate learning outcomes while maintaining consistency between the conceptual variables, instructional treatment, and empirical measurements.

Data Analysis

The data were analyzed using both descriptive and inferential statistical procedures to evaluate the research hypotheses. Descriptive statistics, particularly means and standard deviations, were calculated to summarize the central tendency and variability of pre-test and post-test scores across instructional conditions and cognitive style categories. Before hypothesis testing, prerequisite analyses were performed to determine whether the data satisfied the assumptions required for parametric analysis. The Kolmogorov-Smirnov test was employed to examine normality, while Levene's test was used to assess the homogeneity of error variances across groups. The homogeneity of regression slopes was also examined because ANCOVA requires the relationship between the covariate and dependent variable to remain sufficiently consistent across treatment conditions. After these assumptions were satisfied, the three research hypotheses were evaluated simultaneously using a Two-Way Analysis of Covariance (ANCOVA). In this model, post-test mathematical concept understanding scores served as the dependent variable, pre-test scores were entered as the covariate, and learning model (DMM-TPS versus conventional TPS) and cognitive style (Visualizer versus Verbalizer) were treated as fixed factors. The main effect of the learning model determined whether DMM-TPS produced significantly different post-test achievement after controlling for initial ability, whereas the main effect of cognitive style examined whether adjusted achievement differed between Visualizers and Verbalizers. The learning model × cognitive style interaction was used to determine whether the effectiveness of DMM-TPS depended on cognitive style, thereby directly evaluating the proposed moderating relationship within the same statistical model. Statistical significance was established at $\alpha = 0.05$, while partial eta squared ($\eta^2 p$) was reported as an effect-size measure to complement significance testing and provide information regarding the practical magnitude of the observed effects.

Research Procedure

The research procedure was organized into preparation, pre-intervention assessment, instructional intervention, post-intervention assessment, and data analysis stages. During the preparation stage, the researchers developed the DMM-TPS teaching module, SPLDV learning activities, mathematical concept understanding test, cognitive style questionnaire, scoring rubric, and documentation sheets. The research instruments and instructional materials were reviewed before implementation to ensure their alignment with the study objectives and the mathematical content being investigated. At the pre-intervention stage, students completed the cognitive style questionnaire and were subsequently classified as Visualizers or Verbalizers according to the predetermined scoring criteria. Both the experimental and control groups then completed the pre-test to establish their initial level of mathematical concept understanding before receiving instruction. During the intervention, the experimental group learned SPLDV through DMM-TPS, in which students first engaged in individual mathematical thinking and organized relevant concepts using digital mind maps during the Think stage. In the Pair stage, students discussed their mind maps and mathematical reasoning with partners, compared conceptual relationships, identified inconsistencies, and collaboratively refined their understanding. During the Share stage, students communicated the results of their discussions and conceptual representations to the class, enabling further clarification and collective evaluation of mathematical ideas. The control group studied the same SPLDV content through conventional TPS following the Think, Pair, and Share sequence but without the use of Digital Mind Mapping, thereby maintaining TPS as the common pedagogical structure across conditions. Following completion of the instructional intervention, both groups completed the same post-intervention assessment framework under comparable conditions, while documentation of classroom implementation was compiled to support treatment-fidelity evaluation. Finally, all pre-test, post-test, cognitive-style, and implementation data were organized and analyzed using the predetermined statistical procedures to determine the effect of DMM-TPS, differences associated with cognitive style, and the interaction between instructional model and cognitive style.

Figure 1 illustrates the overall research method flow, beginning with the application of a quasi-experimental nonequivalent control group design and the selection of 60 participants from two intact classes. The participants were equally distributed between the experimental DMM-TPS group and the conventional TPS control group and were further classified according to Visualizer and Verbalizer cognitive styles. Each learning-model group consisted of 30 students, including 15 Visualizers and 15 Verbalizers, providing a balanced structure for examining both main and interaction effects. Before the intervention, students completed a cognitive style questionnaire for classification and a pre-test to establish their initial level of mathematical concept understanding. During the intervention, the experimental group received Digital Mind Mapping-integrated Think-Pair-Share (DMM-TPS), whereas the control group followed the same TPS sequence without Digital Mind Mapping. This design allowed the contribution of Digital Mind Mapping to be examined while maintaining TPS as the common cooperative learning framework across both groups. Data were collected using pre-test and post-test assessments, a cognitive style questionnaire, teaching modules, and implementation documentation. Classroom documentation was also used to monitor treatment fidelity and ensure that the instructional procedures were implemented consistently with the research design. Following the intervention, both groups completed the post-test under comparable assessment conditions. The collected data were subsequently analyzed using Two-Way ANCOVA, with pre-test scores as the covariate, learning model and cognitive style as fixed factors, and post-test scores as the dependent variable. This analytical framework simultaneously examined the main effect of the learning model, the main effect of cognitive style, and the interaction between these two factors after controlling for students' initial ability. Accordingly, the research flow provides a systematic framework for determining the effectiveness of DMM-TPS and evaluating whether its effect on students' mathematical concept understanding varies between Visualizer and Verbalizer students.

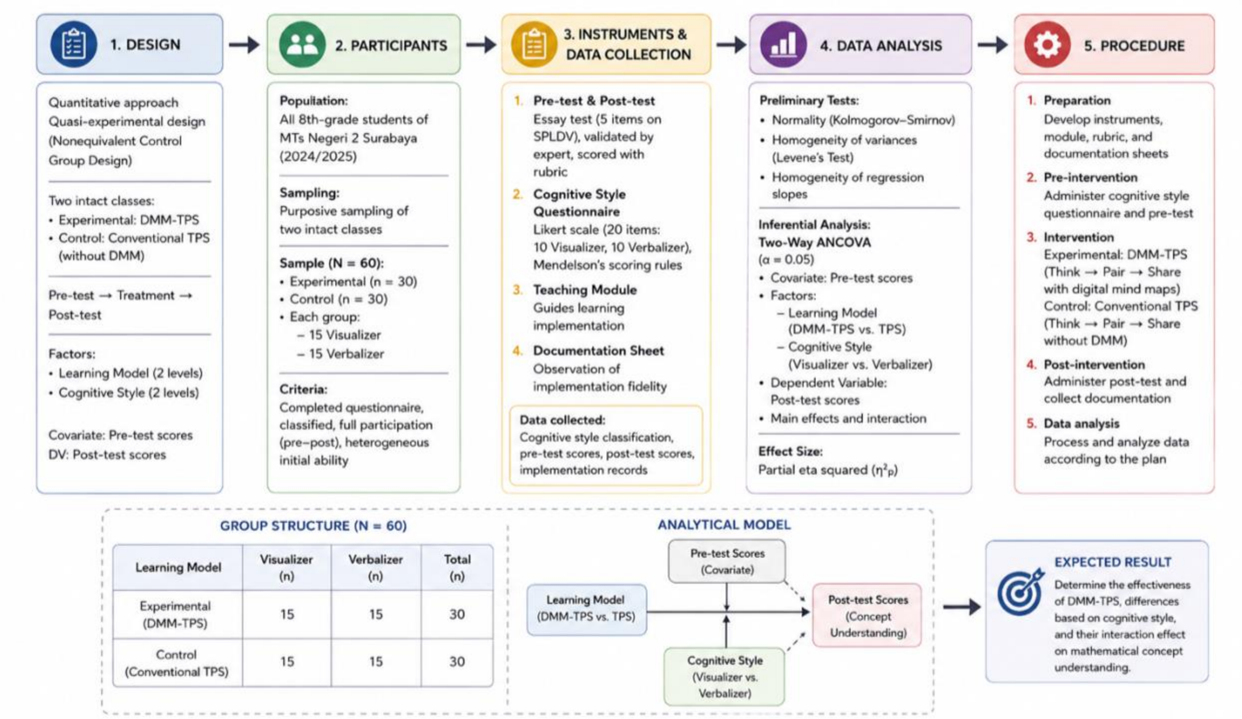

Figure 1. Research Method Flow

RESULTS AND DISCUSSION

Results

This study focuses on the implementation of two learning models. TPS cooperative learning with digital mind mapping integration and TPS learning without digital mind mapping integration with 210 students as the initial subjects who participated in the study. From this pool, the final sample was selected using purposive sampling (selecting intact classes based on the availability of heterogeneous initial abilities and consistent scheduling), resulting in 60 research subjects, consisting of 30 students with visualizer and 30 with verbalizer cognitive styles. The cognitive style questionnaire (Appendix II) used for subject classification underwent content validation by experts and demonstrated adequate reliability (Cronbach's $\alpha > 0.70$), ensuring consistent classification of students into Visualizer and Verbalizer categories. The research was conducted from April 13 to May 8, covering approximately 8 learning meetings. Each meeting lasted 2 x 40 minutes. To ensure treatment fidelity, observational sheets were used to monitor whether the instructional steps in both the experimental and control groups were delivered consistently as planned. The specific SPLDV sub-topics (solving using substitution, elimination, and mixed methods) are detailed in the instructional procedure section of the Methods, rather than presented here. The following are the results of the pre-post test of the research subjects who had participated in the learning process in the control and experimental classes:

Table 1. Results of the pre-post test of the research subjects

No.	Group	Subject	Pre-Test	Post-Test	No.	Group	Subject	Pre-Test	Post-Test
1	Control	VB1	45	63	31	Experimental	VB16	72	84
2	Control	VB2	54	72	32	Experimental	VB17	65	88
3	Control	VB3	52	80	33	Experimental	VB18	61	94
4	Control	VB4	59	88	34	Experimental	VB19	74	95
5	Control	VB5	62	82	35	Experimental	VB20	71	95
6	Control	VB6	68	79	36	Experimental	VB21	51	66
7	Control	VB7	57	87	37	Experimental	VB22	60	78
8	Control	VB8	72	85	38	Experimental	VB23	59	85
9	Control	VB9	53	66	39	Experimental	VB24	56	83
10	Control	VB10	69	95	40	Experimental	VB25	54	74
11	Control	VB11	66	77	41	Experimental	VB26	64	90
12	Control	VB12	75	95	42	Experimental	VB27	74	85
13	Control	VB13	74	95	43	Experimental	VB28	64	95
14	Control	VB14	56	81	44	Experimental	VB29	60	87
15	Control	VB15	61	71	45	Experimental	VB30	51	65
16	Control	VS1	50	68	46	Experimental	VS16	57	97
17	Control	VS2	62	76	47	Experimental	VS17	45	65
18	Control	VS3	48	73	48	Experimental	VS18	72	100
19	Control	VS4	62	83	49	Experimental	VS19	48	80
20	Control	VS5	57	67	50	Experimental	VS20	61	100
21	Control	VS6	62	79	51	Experimental	VS21	65	100
22	Control	VS7	63	77	52	Experimental	VS22	46	58
23	Control	VS8	55	75	53	Experimental	VS23	70	98
24	Control	VS9	66	90	54	Experimental	VS24	69	100
25	Control	VS10	73	90	55	Experimental	VS25	61	88
26	Control	VS11	71	89	56	Experimental	VS26	59	79
27	Control	VS12	69	90	57	Experimental	VS27	58	72
28	Control	VS13	73	90	58	Experimental	VS28	57	93
29	Control	VS14	61	78	59	Experimental	VS29	47	60
30	Control	VS15	52	86	60	Experimental	VS30	69	95

Further information regarding the table above: 1) the control class is an implementation of learning using the TPS cooperative learning method without digital mind mapping integration, 2) the experimental class is an implementation of learning using the TPS cooperative learning method with digital mind mapping integration, 3) the research subjects have 2 categories, namely VB or verbalizer and VS or visualizer. In the primary data processing process of the research using SPSS, the normality values were obtained as follows.

Table 2. Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Standardized Residual for Post_test	,073	60	,200*	,986	60	,723

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Table 2 presents the normality test results for the standardized residuals. Given the total sample size (n=60, with 30 per group), the Shapiro-Wilk test serves as the primary reference for normality, as it is generally preferred for smaller to moderate sample sizes (n < 50 per group). The significance value of 0.723 (> 0.05) confirms that the residuals are normally distributed. Following this, Levene's test was conducted to check the homogeneity of variances, and the assumption was met, permitting the use of parametric inferential statistics. The next step in processing the primary data is the categories between subjects and research factors. This can be visualized in the table below.

Table 3. Between-Subjects Factors

Factor		Value Label	N
Learning Model	1	COntrol	30
	2	Experimental	30
Cognitive Style	1	Visualizer	30
	2	Verbalizer	30

Based on the table above, the learning models were categorized into two categories: control and experimental, with 30 subjects each. Meanwhile, cognitive styles were categorized into two categories: visualizers and verbalizers, with 30 subjects each.

Table 4. Descriptive Statistics

Dependent Variable: Post - Test

Learning Model	Cognitive Style	Mean	Std. Deviation	N
Control	Visualizer	80,73	8,172	15
	Verbalizer	81,07	10,145	15
	Total	80,90	9,053	30
Experimental	Visualizer	85,67	15,500	15
	Verbalizer	84,27	9,809	15
	Total	84,97	12,764	30
Total	Visualizer	83,20	12,430	30
	Verbalizer	82,67	9,939	30
	Total	82,93	11,161	60

Table 4 presents the descriptive statistics for post-test scores across learning models and cognitive style groups. For the learning model comparison, the experimental group achieved a mean of 84.97 (SD = 12.764), while the control group achieved 80.90 (SD = 9.053), showing a descriptive mean difference of 4.07 points. Regarding cognitive styles within the control group, Visualizers scored 80.73 (SD = 8.172) and Verbalizers scored 81.07 (SD = 10.145), reflecting a negligible descriptive gap of 0.34 points. In the experimental group, Visualizers scored 85.67 (SD = 15.500) and Verbalizers scored 84.27 (SD = 9.809), with a descriptive difference of 1.40 points. Across both groups combined, Visualizers had an overall mean of 83.20 (SD = 12.430) and Verbalizers 82.67 (SD = 9.939), a descriptive difference of only 0.53 points. Crucially, these descriptive comparisons are purely observational and do not imply inferential significance; all claims regarding effectiveness or statistically meaningful differences between groups are reserved for the subsequent ANCOVA inferential analysis.

Based on the table above, the interpretation of cognitive styles is based on the experimental group. In the experimental group, students with a visualizer cognitive style obtained an average post-test score of 85.67 with a standard deviation of 15.500. Meanwhile, students with a verbalizer cognitive style obtained an average post-test score of 84.27 with a standard deviation of 9.809. These results indicate that visualizer students had a slightly higher average score than verbalizer students, with a difference of 1.40 points. Nevertheless, both groups demonstrated relatively high learning outcomes compared to the control group. Based on the table above, the interpretation of cognitive styles as a whole. When viewed from the entire research sample without different learning models, students with a visualizer cognitive style obtained an average post-test score of 83.20 with a standard deviation of 12.430. Meanwhile, students with a verbalizer cognitive style obtained an average post-test score of 82.67 with a standard deviation of 9.939. The average difference between the two groups was only 0.53 points, so descriptively it can be said that the learning outcomes of visualizer and verbalizer students are relatively the same. Based on the table above, the overall interpretation of the post-test data. Overall, the 60 students who were part of the research sample obtained an average post-test score of 82.93 with a standard deviation of 11.161. This average value indicates that student learning outcomes after participating in the learning are in a fairly good category. The variation in scores indicated by the standard deviation value of 11.161 indicates differences in learning outcomes among students, although in general, learning outcomes are around the average value.

Table 5. Levene's Test of Equality of Error Variances

Dependent Variable: Post - Test			
F	df1	df2	Sig.
1,606	3	56	,198

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

Returning to the discussion of the Levene's Test, before conducting further analysis using parametric statistics, a homogeneity of variance test was first performed using Levene's Test of Equality of Error Variances. The test results showed an F-value of 1.606 with df1 = 3 and df2 = 56, and a significance value (Sig.) of 0.198. This significance value is greater than the established significance level ($\alpha = 0.05$), which is $0.198 > 0.05$. Therefore, the null hypothesis (H_0) stating that the error variances across groups are equal is not rejected. Therefore, it can be concluded that the variances of post-test scores between groups, as examined based on learning models and cognitive styles, are homogeneous. The results of the primary data homogeneity test can be used to conduct further statistical tests. These results indicate that one of the important assumptions in the analysis of covariance (TWO-WAYS ANCOVA), namely equality of variances between groups, has been met. Therefore, the data is worthy to be continued to the hypothesis testing stage using TWO WAYS ANCOVA to determine the effect of learning models, cognitive styles, and the interaction of the two on student learning outcomes after controlling for pre-test scores.

Table 6. Tests of Between Subjectives Effects (Dependent Variable: Post-Test Score)

Source	Type III Sum of Squares	df	Mean Square	F	p	Partial η^2	Observed Power
Corrected Model	4402.272	4	1100.568	20.537	< .001	.599	1.000
Intercept	469.076	1	469.076	8.753	.005	.137	.828
Pre-Test	4138.672	1	4138.672	77.228	< .001	.584	1.000
Learning Model	370.633	1	370.633	6.916	.011	.112	.734
Cognitive Style	75.483	1	75.483	1.409	.240	.025	.215
Learning Model × Cognitive Style	104.612	1	104.612	1.952	.168	.034	.279
Error	2947.461	55	53.590	—	—	—	—
Total	420026.000	60	—	—	—	—	—
Corrected Total	7349.733	59	—	—	—	—	—

Based on the results of the two-way ANCOVA test in the Tests of Between-Subjects Effects table, it can be seen that digital mind mapping-based learning in the Think Pair Share (TPS) cooperative model significantly impacted students' understanding of mathematical concepts. This is indicated by a significance value of 0.011 for the Learning_Model variable, which is less than 0.05.

Thus, the learning implemented in this study can be considered effective in improving students' understanding of mathematical concepts. Furthermore, based on the analysis of the Cognitive_Style variable, a significance value of 0.240 was obtained, greater than 0.05. These results indicate that there was no significant difference in learning outcomes between visualizer and verbalizer students after participating in digital mind mapping-based learning in the TPS cooperative model. This means that both cognitive style groups achieved relatively similar learning outcomes (Yunita & Nirawana, 2025).

Furthermore, the interaction between Learning_Model and Cognitive_Style obtained a significance value of 0.168, also greater than 0.05. This indicates that there is no significant interaction between learning model and cognitive style on students' understanding of mathematical concepts. In other words, the effectiveness of digital mind mapping learning in the TPS model applies generally, with no significant differences between visualizer and verbalizer students. Overall, the results of this study indicate that digital mind mapping-based learning in the TPS cooperative model is effective in improving students' understanding of mathematical concepts, but this effectiveness is not significantly influenced by differences in students' cognitive styles.

Table 7. Learning Model

Dependent Variable: Post - Test

Learning Model	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Control	80,444[a]	1,338	77,764	83,125
Experimental	85,422[a]	1,338	82,742	88,103

a. Covariates appearing in the model are evaluated at the following values: Pre - Test = 61,12.

Based on the table, learning in the experimental class showed better results than in the control class. The average post-test score in the control class was 80.444, while in the experimental class it was 85.422. This indicates that the integration of digital mind mapping in the Think Pair Share cooperative learning model resulted in higher results in students' understanding of mathematical concepts compared to the learning in the control class. Furthermore, the 95% confidence interval in the control class ranged from 77.764 to 83.125, while in the experimental class it ranged from 82.742 to 88.103. This range of values indicates that student learning outcomes in the experimental class tended to be higher and relatively consistent (Nurmanita et al., 2025). Thus, descriptively, it can be concluded that the integration of digital mind mapping in the Think Pair Share cooperative learning model is effective in improving students' understanding of mathematical concepts. Based on these results, this finding supports the first research question, namely that the implementation of digital mind mapping in the Think Pair Share cooperative model has a positive impact on students' mathematical understanding.

Table 8. Cognitive Style

Dependent Variable: Post - Test

Gaya Kognitif	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Visualizer	84,061[a]	1,340	81,375	86,747
Verbalizer	81,806[a]	1,340	79,120	84,491

a. Covariates appearing in the model are evaluated at the following values: Pre - Test = 61,12.

The Estimated Marginal Means analysis showed that after controlling for the influence of students' initial pre-test ability at an average of 61.12, students with a visualizer cognitive style achieved an average post-test score of 84.061 with a standard error of 1.340. Meanwhile, students with a verbalizer cognitive style achieved an average post-test score of 81.806 with the same standard error of 1.340. Descriptively, visualizer students had a higher average understanding of mathematical concepts than verbalizer students (Herawati et al., 2026). The average difference between the two groups of 2.255 points indicates that visualizer students tended to achieve better learning outcomes after participating in digital mind mapping-based learning in the Think Pair Share (TPS) cooperative model. Furthermore, the 95% confidence interval for the visualizer group ranged from 81.375 to 86.747, while the confidence interval for the verbalizer group ranged from 79.120 to 84.491. The overlapping confidence intervals between the two groups indicate that the average difference in learning outcomes between visualizer and verbalizer students is relatively small. Based on these findings, it can be concluded that digital mind mapping-based learning in the Think Pair Share (TPS) cooperative model can produce good learning outcomes for both visualizer and verbalizer students (Nisa et al., 2025). Although visualizer students demonstrated a higher average understanding of mathematical concepts than verbalizer students, this difference did not indicate a significant gap descriptively. Therefore, the learning model implemented in this study tends to accommodate both cognitive styles relatively equally in improving students' understanding of mathematical concepts.

Table 9. Learning Model * Cognitive Style

Dependent Variable: Post - Test

Learning Model	Cognitive Style	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Control	Visualizer	80,244[a]	1,891	76,454	84,033
	Verbalizer	80,645[a]	1,891	76,855	84,434
Experimental	Visualizer	87,878[a]	1,907	84,057	91,700
	Verbalizer	82,967[a]	1,896	79,167	86,766

a. Covariates appearing in the model are evaluated at the following values: Pre - Test = 61,12.

The Estimated Marginal Means analysis results showed an average post-test score adjusted to control for the influence of students' initial abilities (pre-test) of 61.12. In the control group, students with a visualizer cognitive style obtained an average post-test score of 80.244 with a 95% confidence interval of 76.454 to 84.033. Meanwhile, students with a verbalizer cognitive style obtained an average post-test score of 80.645 with a 95% confidence interval of 76.855 to 84.434. These results indicate that in the control group, the understanding of mathematical concepts of visualizer and verbalizer students was relatively similar. In the experimental group, which received digital mind mapping-based learning in the Think Pair Share (TPS) cooperative model, visualizer students obtained an average post-test score of 87.878 with a 95% confidence interval of 84.057 to 91.700. The verbalizer students achieved an average post-test score of 82.967, with a 95% confidence interval between 79.167 and 86.766. These results indicate that the visualizer students in the experimental group had a higher average understanding of mathematical concepts than the verbalizer students (Nisa et al., 2025).

When compared based on the learning model, both visualizer and verbalizer students in the experimental group demonstrated higher average post-test scores than the control group. For visualizer students, the average score increased from 80.244 in the control group to 87.878 in the experimental group. Meanwhile, for verbalizer students, the average score increased from 80.645 in the control group to 82.967 in the experimental group. Descriptively, these results indicate that the implementation of digital mind mapping-based learning within the Think Pair Share (TPS) cooperative model resulted in a trend toward improved students' understanding of mathematical concepts compared to the control group (Dau et al., 2025). This improvement was evident in both cognitive style groups, visualizers and verbalizers. However, greater improvement was observed in visualizer students than in verbalizer students. Thus, digital mind mapping-based learning within the Think Pair Share (TPS) cooperative model demonstrates good potential for improving students' understanding of mathematical concepts. Furthermore, although visualizer students tended to achieve higher average learning outcomes than verbalizer students, both cognitive style groups still benefited from the implementation of this learning model (Handayani & Mulyono, 2025).

Discussion

The findings demonstrate that integrating Digital Mind Mapping into the Think-Pair-Share cooperative model produced a statistically significant effect on students' mathematical concept understanding after differences in initial achievement were controlled. The experimental group obtained a raw post-test mean of 84.97 compared with 80.90 in the control group, while the ANCOVA-adjusted means increased this difference to 85.422 and 80.444, respectively. This finding indicates that incorporating a digital representational tool into an established cooperative structure can provide additional learning benefits beyond those generated by TPS instruction alone. Such an effect can be interpreted through the complementary functions of DMM and TPS, as digital mind maps externalize relationships among mathematical ideas while cooperative interaction provides opportunities to explain, negotiate, and reconstruct those relationships. This interpretation is consistent with previous evidence that mind-mapping-based instruction can positively influence students' cognitive learning outcomes by facilitating the organization and integration of knowledge (Y. Shi et al., 2023). Related research has also demonstrated that online collaborative mind mapping can support interaction and knowledge construction, suggesting that visual knowledge organization becomes particularly productive when embedded within collaborative learning activities (Araujo et al., 2021). Similarly, technology-enhanced collaborative mathematics environments have been associated with improvements in mathematical reasoning because digital representations and peer interaction jointly support the construction of mathematical meaning (Demir & Zengin, 2023). The present study extends these findings by demonstrating this complementary mechanism within SPLDV learning and, importantly, by comparing DMM-TPS against TPS without digital mind mapping rather than against an entirely unrelated conventional pedagogy. Therefore, the significant treatment effect is more plausibly associated with the added contribution of digital mind mapping within the shared TPS structure, although the quasi-experimental design does not establish causality as strongly as individual random assignment would. Taken together, these findings position DMM-TPS as a potentially effective technology-enhanced cooperative approach for strengthening mathematical concept understanding through the coordination of visual organization, individual reasoning, and peer-supported knowledge construction.

The pedagogical contribution of DMM-TPS becomes particularly relevant when the representational demands of SPLDV are considered, because conceptual understanding requires students to coordinate equations, solution procedures, relationships between variables, and interpretations of mathematical solutions. Students who rely primarily on procedural routines may successfully execute substitution or elimination algorithms without developing an integrated understanding of why the procedures produce equivalent solutions. Digital mind mapping may address this difficulty by enabling students to externalize conceptual connections and organize mathematical information into a relational structure rather than treating formulas and procedures as isolated elements. This mechanism is compatible with earlier evidence that mind mapping can support memory, creativity, and conceptual organization by encouraging learners to establish explicit connections among related ideas. More recent evidence from mind-mapping research similarly indicates that digital forms offer flexibility for organizing, revising, and connecting knowledge, making them particularly relevant to learning environments that require active conceptual construction. The effectiveness observed in the present study also parallels findings from technology-supported geometry instruction, where digital representations such as GeoGebra have been shown to facilitate conceptual understanding by making abstract mathematical relationships more accessible (Gurmu et al., 2024). Nevertheless, DMM differs pedagogically from dynamic mathematics software because its primary function is not to simulate mathematical objects but to help students construct an explicit network of relationships among concepts, procedures, representations, and explanations. When this organizational function is incorporated into the Think phase of TPS, students can establish an initial conceptual structure before discussing it with peers during Pair and communicating it during Share. Consequently, the observed improvement may reflect a sequence of cognitive externalization, peer elaboration, and collective clarification rather than the isolated influence of technology itself. This interpretation reinforces the broader argument that digital technology becomes educationally meaningful when its affordances are deliberately aligned with pedagogical processes instead of being introduced merely as an additional classroom resource.

A second important finding concerns cognitive style, for which the ANCOVA produced no statistically significant main effect between Visualizer and Verbalizer students (p = .240). Although the adjusted mean for Visualizers (84.061) exceeded that of Verbalizers (81.806) by 2.255 points, this descriptive difference was insufficient to establish a reliable cognitive-style effect within the present sample. This result is noteworthy because theoretical accounts of Visualizer–Verbalizer differences suggest that learners vary in their preferences for graphical-spatial versus linguistic forms of information processing. From that perspective, one might expect Digital Mind Mapping to disproportionately benefit Visualizers because its graphical organization corresponds more directly to their preferred mode of information representation. Previous studies have indeed suggested that visually structured learning environments can provide advantages for Visualizer learners when information is represented through diagrams and organized visual relationships (Islami & Triyana, 2024). The absence of a significant overall cognitive-style effect in the current study, however, suggests that representational preference alone may not determine achievement when students participate in an instructional environment combining visual and verbal opportunities. TPS requires students to think individually, articulate ideas to partners, listen to alternative explanations, and communicate reasoning publicly, thereby introducing substantial verbal processing alongside the visual organization offered by digital mind mapping. This multimodal structure may have enabled Visualizers to capitalize on graphical organization while allowing Verbalizers to construct meaning through discussion and verbal elaboration, reducing the possibility that one cognitive group would systematically outperform the other. The result should not be interpreted as evidence that cognitive styles are irrelevant to mathematical learning, but rather as evidence that no statistically reliable difference in adjusted achievement between the two classifications was detected under the conditions examined. Accordingly, the findings support a more cautious pedagogical perspective in which cognitive diversity is acknowledged without assuming that students necessarily require separate instructional pathways solely on the basis of Visualizer–Verbalizer classification.

The interaction analysis provides an even more important contribution because the Learning Model × Cognitive Style effect was not statistically significant (p = .168), indicating insufficient evidence that the effect of DMM-TPS differed systematically between Visualizer and Verbalizer students. The adjusted subgroup means nevertheless revealed an interesting descriptive pattern: Visualizers increased from 80.244 under control TPS to 87.878 under DMM-TPS, whereas Verbalizers increased from 80.645 to 82.967. Thus, the descriptive treatment contrast was considerably larger among Visualizers, which is theoretically plausible given the visually structured nature of digital mind mapping. However, because the interaction did not reach the predetermined significance threshold, this pattern cannot be interpreted as statistical confirmation that Visualizers benefited more from the intervention. This distinction is essential because a larger numerical difference between subgroup means does not by itself demonstrate moderation, particularly when subgroup sizes are limited to 15 students per cell and within-group variability is substantial. The finding therefore differs from interpretations that rigidly match instructional modalities to presumed learning preferences, because the present evidence does not demonstrate that DMM-TPS effectiveness is conditional on Visualizer–Verbalizer status. Instead, it is more compatible with research emphasizing multimodal and technology-enhanced collaborative learning environments in which students engage with mathematical ideas through multiple representational and communicative pathways (Aksu & Zengin, 2022; Zengin, 2023). By combining visual mapping with individual reasoning and verbal peer interaction, DMM-TPS may provide sufficient representational flexibility for students to use different pathways while participating in the same instructional structure. At the same time, the non-significant interaction must not be interpreted as proof of equivalence between cognitive styles, because demonstrating equivalent treatment effects would require an equivalence or non-inferiority framework rather than conventional null-hypothesis significance testing. Future studies with larger subgroup samples may determine whether the descriptive advantage observed among Visualizers represents a replicable differential response or merely sampling variation. Consequently, the present evidence supports the more defensible conclusion that DMM-TPS generated learning benefits without a statistically detectable moderating effect of cognitive style in this sample.

Viewed collectively, the findings shift the principal explanatory emphasis from matching instruction to cognitive-style categories toward designing learning environments that integrate complementary technological and cooperative processes. The significant main effect of the learning model, combined with non-significant cognitive-style and interaction effects, suggests that instructional design was the clearest statistical contributor to post-test differences after initial achievement was controlled. This pattern corresponds with broader research showing that technology-enhanced collaborative learning can strengthen mathematics learning when technological affordances are deliberately connected to interaction, reasoning, and knowledge construction (Demir & Zengin, 2023). It is also consistent with evidence that collaborative technologies can facilitate mathematical reasoning by creating shared spaces in which students represent, discuss, and revise mathematical ideas (Aksu & Zengin, 2022). The present study advances this literature by identifying Digital Mind Mapping as a potentially useful representational component within TPS rather than treating technology and cooperative learning as separate pedagogical interventions. From a classroom perspective, the findings suggest that teachers may gain greater instructional value from optimizing how students construct digital maps, explain conceptual connections, question partners' reasoning, and revise representations than from assigning fundamentally different instructional models according to cognitive-style labels. The adjusted experimental-control difference of approximately 4.98 points further indicates that controlling for baseline achievement does not eliminate the advantage associated with DMM-TPS, strengthening the interpretation that the intervention contributed meaningfully to students' subsequent conceptual performance. Nevertheless, the magnitude of the effect should be interpreted alongside the reported effect size, confidence intervals, sample characteristics, and quasi-experimental design rather than being characterized as transformative solely because statistical significance was achieved. The findings therefore contribute to mathematics education by demonstrating that an integrated visual-cooperative instructional environment can improve SPLDV concept understanding while showing no statistically detectable evidence that its effectiveness depends on Visualizer–Verbalizer cognitive style. Overall, the study supports a shift toward inclusive technology-enhanced mathematics instruction in which digital representation and structured collaboration are treated as mutually reinforcing pedagogical resources capable of supporting heterogeneous learners within a common classroom environment.

Implications

The findings provide theoretical and practical implications for technology-enhanced mathematics instruction. The significant effect of Digital Mind Mapping integrated with Think-Pair-Share (DMM-TPS) indicates that combining visual organization with collaborative interaction can strengthen students' mathematical concept understanding. The non-significant effect of cognitive style suggests that Visualizer–Verbalizer differences were not a decisive factor in students' achievement within the learning environment examined. Likewise, the non-significant interaction indicates no sufficient evidence that DMM-TPS effectiveness differed between Visualizers and Verbalizers. These findings encourage teachers to prioritize effective instructional design rather than rigidly matching instruction to cognitive-style classifications. Digital mind mapping can support students in organizing SPLDV concepts, while TPS facilitates discussion, explanation, and collaborative refinement of mathematical ideas. This combination provides complementary visual and verbal learning opportunities within the same classroom. Consequently, teachers may implement DMM-TPS without separating students into different instructional pathways based solely on cognitive style. Schools can also use this approach to integrate digital technology while maintaining meaningful student interaction. Teacher development should therefore emphasize the pedagogical integration of digital tools with structured cooperative learning. Such integration may contribute to more inclusive and flexible mathematics learning environments. Overall, DMM-TPS offers a practical approach for supporting mathematical concept understanding across students with diverse cognitive preferences.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting its findings. The sample was limited to 60 eighth-grade students from a single school, which restricts the generalizability of the results. The use of intact classes and purposive sampling also prevented individual random assignment and may have introduced uncontrolled group differences. Moreover, the relatively small number of students in each cognitive-style subgroup may have limited the statistical power to detect interaction effects. The intervention was conducted over approximately eight meetings, making it difficult to determine whether the observed learning benefits persist over time. The study was also restricted to SPLDV, so the effectiveness of DMM-TPS cannot automatically be generalized to other mathematical topics. In addition, Visualizer and Verbalizer classifications were based primarily on questionnaire responses, which may not fully represent the complexity of students' cognitive processing. Therefore, the non-significant interaction should not be interpreted as evidence of equivalent effects across cognitive styles. Future studies should involve larger samples from multiple schools and educational contexts. Longer interventions accompanied by delayed post-tests are recommended to examine the retention of learning outcomes. Further research could also investigate DMM-TPS across different mathematical topics and outcomes, including reasoning, problem solving, and mathematical representation. Finally, mixed-method and experimental studies with stronger designs are recommended to provide deeper evidence regarding how DMM-TPS supports students with diverse cognitive characteristics.

CONCLUSION

This study demonstrates that Digital Mind Mapping integrated with Think-Pair-Share (DMM-TPS) significantly improves students' mathematical concept understanding of SPLDV after controlling for initial ability (p = .011; partial η^2 = .10). The moderate effect size indicates that integrating visual knowledge organization with cooperative learning provides meaningful pedagogical benefits. Although Visualizer students achieved descriptively higher scores than Verbalizers, cognitive style had no significant effect on learning outcomes. Likewise, the interaction between learning model and cognitive style was not significant, providing no statistical evidence that DMM-TPS effectiveness differed between the two cognitive groups. Thus, cognitive style was not supported as a significant moderator within the present sample. These findings suggest that DMM-TPS can provide visual and collaborative learning opportunities within a common instructional environment without requiring separate learning pathways based solely on cognitive-style classification. However, the non-significant interaction should not be interpreted as evidence that the specific cognitive needs of both groups were equally fulfilled. Overall, DMM-TPS represents a promising alternative for strengthening mathematical concept understanding through technology-enhanced cooperative learning. Nevertheless, the single-school setting, limited sample, and quasi-experimental design constrain the generalizability of the findings. Further studies involving larger and more diverse populations are therefore recommended to confirm its effectiveness across different mathematics learning contexts.

AUTHOR CONTRIBUTIONS STATEMENT

Akhyat Khalimy Afif Romadlon: Conceptualization, methodology, investigation, data collection, formal analysis, and writing original draft. Baiduri: Conceptualization, methodology, validation, supervision, and writing review and editing. Agung Dediliawan Ismail: Validation, formal analysis, supervision, and writing review and editing. All authors contributed to the interpretation of the findings, critically reviewed the manuscript, and approved the final version for publication.

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