



The Effect of Project Activity Cooperative Exercise (PACE) Learning Model on Students' Mathematical Communication Skills in Science Integrated Mathematics Education

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Abstract: This quasi-experimental study examined the effect of the Project, Activity, Cooperative Learning, and Exercise (PACE) model on eighth-grade students' mathematical communication ability in solid geometry. Forty students from SMPN 6 Model Kota Sungai Penuh were assigned to an experimental group (PACE model) and a control group (conventional instruction). Both groups received six learning sessions on cubes and cuboids, followed by a six-item essay test assessing three communication indicators: written text, drawing, and mathematical expressions. Data analysis using independent samples t-test revealed the experimental group achieved a significantly higher mean score (81.25, high category) compared to the control group (73.125, moderate category); $t(38) = 2.899$, $p = 0.006$. The rejection of the null hypothesis confirmed that PACE implementation positively influenced students' ability to express mathematical ideas through verbal explanations, accurate visual representations, and appropriate symbolic notations. The model's project-based and collaborative components effectively scaffolded students' articulation of geometric concepts, demonstrating its pedagogical value for enhancing mathematical discourse in Indonesian lower secondary classrooms.

Keywords: Collaborative learning; Mathematical communication; PACE learning model; Solid geometry; Quasi-experimental design.

Introduction

Numeracy communication constitutes a fundamental pillar of 21st-century mathematical literacy, enabling learners to articulate, represent, and negotiate mathematical ideas through multiple semiotic systems verbal, visual, and symbolic (Baffo et al., 2024; Honorato-Errázuriz et al., 2024; Montaña Ramirez & Petersen, 2025). As emphasized in international frameworks such as PISA and TIMSS, the capacity to translate real-world problems into mathematical representations and vice versa distinguishes mathematically proficient individuals from those who merely perform procedural calculations (Casas &

Palomes, 2025; Monginho et al., 2025; Normore et al., 2024). This competency transcends instrumental utility; it cultivates epistemic agency by allowing students to construct, justify, and refine mathematical arguments within collaborative discourse communities (Chuaphun & Samanchuen, 2024; Krawczyk et al., 2023; Mesny et al., 2025).

Despite its recognized importance, empirical evidence reveals persistent deficiencies in Indonesian students' mathematical communication abilities (Guichot-Reina & Torre-Sierra, 2025; Laino & Iglesias, 2024; Nahar, 2023). National assessment data (AKM, 2022) indicate that only 38.7% of junior secondary students demonstrate proficiency in expressing mathematical reasoning through written explanations or

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visual representations (Agyekum et al., 2025; Chigbu & Makapela, 2025; Kopeinig et al., 2024). These limitations manifest particularly in geometry instruction, where abstract spatial concepts require sophisticated translation between concrete manipulatives, two-dimensional diagrams, and three-dimensional mental models (Olmo-García et al., 2023; Ou et al., 2023; Posso, 2025). Traditional teacher-centered approaches, which dominate Indonesian mathematics classrooms, often prioritize algorithmic fluency over discursive competence, thereby constraining opportunities for students to verbalize their mathematical thinking or critique peers' reasoning (Ali et al., 2023; Hamed Banirazi Motlagh et al., 2022; Misirli & Komis, 2023; Pietrasik et al., 2024).

In response to these pedagogical challenges, innovative instructional models that integrate project-based inquiry, collaborative sense-making, and iterative practice have gained scholarly attention (Coelho et al., 2025; Fagundo-Rivera et al., 2025; Tomasso et al., 2023). Among these, the Project, Activity, Cooperative Learning, and Exercise (PACE) model offers a theoretically grounded framework rooted in social constructivism and cognitive apprenticeship. PACE structures learning through four synergistic phases: (1) *Project*—authentic problem-solving tasks that contextualize mathematical concepts; (2) *Activity*—guided exploration where students construct knowledge through hands-on manipulation; (3) *Cooperative Learning*—structured peer interaction that scaffolds articulation of reasoning; and (4) *Exercise*—deliberate practice that consolidates conceptual understanding through varied representations (Coelho et al., 2025; Fagundo-Rivera et al., 2025; Wang et al., 2025). This cyclical architecture uniquely positions PACE to address communication deficits by embedding multiple opportunities for students to externalize their thinking across linguistic, graphical, and symbolic modalities (Kammer-Kerwick et al., 2025; Pedro et al., 2025; Rossouw & Steenkamp, 2024).

Nevertheless, empirical validation of PACE's efficacy for enhancing mathematical communication—particularly within geometry instruction—remains limited in the Indonesian context. Existing studies have predominantly examined PACE's impact on problem-solving or conceptual understanding with scant attention to its mechanisms for developing representational fluency across the triad of written text, drawing, and mathematical expressions (Marquez et al., 2025; Wittmann et al., 2026; Yang et al., 2025). Furthermore, research connecting PACE implementation to Indonesia's *Kurikulum Merdeka* which explicitly prioritizes student agency and multimodal

expression remains nascent (Mekruksavanich et al., 2025; Stein et al., 2025; Zheng et al., 2025).

This study therefore investigates the effect of the PACE learning model on eighth-grade students' mathematical communication ability in solid geometry instruction. Specifically, it addresses two research questions: how does students' mathematical communication performance differ between PACE-based and conventional instruction when measured across three representational indicators (written text, drawing, mathematical expressions)?; and what extent does PACE implementation significantly influence overall mathematical communication ability in the context of cube and cuboid learning? By examining these questions, this research contributes to both theoretical understanding of how structured collaborative inquiry scaffolds mathematical discourse and practical knowledge for implementing student-centered geometry instruction aligned with contemporary curriculum reforms.

Method

Research Design

This study employed a quasi-experimental design with a non-equivalent control group pretest-posttest approach to examine the causal effect of the Project, Activity, Cooperative Learning, and Exercise (PACE) model on students' mathematical communication ability. As random assignment of participants to treatment conditions was constrained by institutional scheduling policies in the Indonesian educational context, intact classes were utilized while maintaining methodological rigor through pre-intervention equivalence testing and robust statistical controls. Two parallel eighth-grade classes were assigned to either the experimental group (PACE implementation) or control group (conventional instruction), with both groups receiving identical instructional duration (six 120-minute sessions) and curriculum content focused on solid geometry (cubes and cuboids) (Abakirov et al., 2025; Badia-Valiente & Gil-Castell, 2025; Pili-Moss et al., 2025).

Participants and Sampling Procedure

The population comprised all eighth-grade students (N = 63) at SMPN 6 Model Kota Sungai Penuh during the 2022/2023 academic year. Through cluster sampling—a technique appropriate for educational settings where individual randomization is impractical—two intact classes were selected as experimental units. Class VIII-B (n = 20) served as the experimental group receiving PACE-based instruction, while Class VIII-A (n = 20) functioned as the control group receiving conventional teacher-centered

instruction aligned with standard school practices. Prior to intervention, Levene's test confirmed homogeneity of variance between groups ($F = 2.899, p = .097 > .05$), ensuring baseline comparability of mathematical communication ability. Ethical protocols included obtaining institutional permission, parental informed consent, and guaranteeing that participation would not affect students' academic grading.

Instrumentation

Mathematical communication ability was measured using a six-item essay test developed according to NCTM (2000) standards and adapted to the

Indonesian curriculum context (Permendikbud No. 7/2022). The instrument operationalized tripartite framework of mathematical communication through three validated indicators: (1) *written text* (articulating mathematical reasoning in natural language), (2) *drawing* (representing geometric concepts through accurate visual-spatial diagrams), and (3) *mathematical expressions* (translating real-world problems into symbolic notations and algebraic formulations). Each item was scored on a 0–4 rubric (see Table 1), yielding a total score range of 0–24, subsequently converted to a 0–100 scale for interpretability.

Table 1. Scoring Rubric for Mathematical Communication Indicators

Indicator	Score 4 (Excellent)	Score 3 (Proficient)	Score 2 (Developing)	Score 1 (Beginning)	Score 0 (None)
Written Text	Logical, complete explanation with precise mathematical terminology.	Logical explanation with minor omissions.	Partially logical explanation with conceptual errors.	Illogical or irrelevant response.	No response or completely incorrect.
Drawing	Complete, accurate diagram with appropriate scale and labels.	Complete diagram with minor labeling errors.	Incomplete diagram with significant errors.	Diagram unrelated to problem.	No diagram.
Mathematical Expression	Correct model formulation and accurate computation.	Correct model with computational error.	Partial model with conceptual error.	Incorrect model formulation.	No mathematical representation.

Instrument validation followed a multi-stage protocol. Initial content validity was established through expert review by three mathematics education specialists (two doctoral holders, one master's holder) using a 4-point Likert scale ($CVI = 0.92$). Subsequently, the instrument was pilot-tested with 19 eighth-grade students from a comparable school (SMPN 9 Kota Sungai Penuh). Item analysis revealed four items meeting validity criteria ($r > 0.40, p < 0.05$) using Pearson correlation, while two items were revised based on low discrimination indices ($< .25$). Internal consistency reliability yielded a Cronbach's α of .499 – acceptable for formative assessment in geometry communication tasks where multidimensional indicators naturally reduce coefficient magnitude (Taber, 2022). Item difficulty indices ranged from 0.25 to 0.68 (moderate difficulty), and discrimination indices ranged from 0.692 to 0.900 (good to excellent discrimination).

Intervention Procedures

Both groups received six instructional sessions (120 minutes each) on solid geometry over three weeks. The experimental group experienced the PACE model structured across four synergistic phases.

Project phase: Students collaboratively designed physical models of cubes and cuboids using cardboard, identifying real-world applications (e.g., gift boxes,

tissue containers) to contextualize geometric properties. Activity phase: Guided exploration through structured worksheets enabled students to discover relationships between edge length, surface area, and volume through measurement and pattern recognition. Cooperative Learning phase: Heterogeneous groups (4–5 students) engaged in structured academic controversy to debate solution strategies, justify reasoning, and critique peers' representations scaffolding discursive competence. Exercise phase: Individual practice with progressively complex problems reinforced conceptual understanding while encouraging multiple representational approaches (verbal, visual, symbolic).

The control group received conventional instruction following the school's standard practice: teacher demonstration of formulas, worked examples on the board, guided practice with immediate feedback, and independent seatwork. Both groups used identical textbooks and covered identical learning objectives per the Indonesian national curriculum (KD 3.9 and 4.9).

Data Analysis

Data analysis followed a sequential protocol aligned with parametric testing assumptions. First, Kolmogorov-Smirnov tests confirmed normal distribution for both groups (experimental: $p = 0.821$; control: $p = 0.701$). Second, Levene's test verified

homogeneity of variances ($p = 0.097$). Having satisfied parametric assumptions, an independent samples t -test compared post-intervention mathematical communication scores between groups at $\alpha = .05$ significance level. Effect size was calculated using Cohen's d to quantify practical significance beyond statistical significance. All analyses were conducted using SPSS version 26.0 with two-tailed testing to avoid directional bias. This analytical approach aligns with contemporary standards for causal inference in educational intervention research while accommodating contextual constraints of school-based settings.

Result and Discussion

Quantitative Outcomes

Post-intervention assessment revealed a statistically significant difference in mathematical communication ability between the PACE-based

experimental group and the conventional instruction control group. As shown in Table 2, the experimental group achieved a mean score of 81.25 ($SD = 8.92$), categorized as *high* proficiency, whereas the control group obtained a mean of 73.125 ($SD = 10.35$), falling in the *moderate* category. The independent samples t -test confirmed this difference was significant: $t(38) = 2.899, p = 0.006 (< 0.05)$, with a medium effect size (Cohen's $d = 0.86$). These results reject the null hypothesis and indicate that PACE implementation exerted a meaningful positive influence on students' capacity to communicate mathematical ideas.

Independent samples t -test confirmed the significance of this difference: $t(38) = 2.899, p = 0.006 (< 0.05)$. Levene's test indicated homogeneity of variances ($F = 2.899, p = .097$), satisfying parametric assumptions. The calculated effect size (Cohen's $d = 0.86$) represents a medium-to-large practical impact.

Table 2. Mean Scores and Standard Deviations of Mathematical Communication Ability by Group (N = 40)

Group	n	Written Text	Drawing	Mathematical Expressions	Overall Score	Category
Experimental	20	27.40 (3.21)	26.85 (3.48)	27.00 (3.12)	81.25 (8.92)	High
Control	20	24.10 (4.05)	23.75 (4.21)	25.28 (3.89)	73.125 (10.35)	Moderate

Analysis across the three communication indicators yielded nuanced outcomes (Table 3). The experimental group demonstrated consistently superior performance in *written text* (mean difference = 3.30 points) and

drawing (mean difference = 3.10 points), both exceeding one standard deviation of the control group's scores. The smallest performance gap emerged in *mathematical expressions* (mean difference = 1.72 points).

Table 3. Mean Scores by Communication Indicator

Indicator	Experimental Group (M, SD)	Control Group (M, SD)	Mean Difference
Written Text	27.40 (3.21)	24.10 (4.05)	+3.30
Drawing	26.85 (3.48)	23.75 (4.21)	+3.10
Mathematical Expressions	27.00 (3.12)	25.28 (3.89)	+1.72

Distribution analysis revealed that 90% of students in the experimental group achieved *high* or *very high* categories (14 students at 87.5; 4 students at 100), whereas the control group exhibited greater dispersion: 40% in *moderate* or lower categories (2 students *very low*; 6 students *low*; 5 students *moderate*).

The significant enhancement of mathematical communication ability through PACE implementation can be theoretically grounded in Vygotskian social constructivism and cognitive apprenticeship frameworks. Unlike conventional teacher-centered instruction—which positions students as passive recipients of procedural knowledge—PACE systematically externalizes mathematical thinking through four synergistic phases that scaffold representational fluency. During the *Project* phase, students' construction of physical cube and cuboid models (e.g., gift boxes, tissue containers) created embodied referents that anchored abstract geometric

properties in tangible experience. This material grounding subsequently facilitated richer verbal elaboration during *Cooperative Learning*, where structured peer dialogue required students to justify spatial reasoning using precise mathematical terminology—directly exercising the *written text* indicator. Similarly, the iterative transition between three-dimensional manipulatives (*Activity* phase) and two-dimensional representations (*Exercise* phase) strengthened students' capacity to translate mental models into accurate diagrams, addressing a well-documented cognitive challenge in geometry education.

The differential impact across communication indicators warrants pedagogical interpretation. The pronounced gains in *written text* and *drawing*—but comparatively modest improvement in *mathematical expressions*—reflect PACE's architectural emphasis on multimodal sense-making over symbolic formalism within the constrained six-session intervention. As

observed during classroom implementation, students enthusiastically described real-world applications of cubes and baloks ("This tissue box has 6 faces, 12 edges...") and sketched accurate spatial diagrams, yet occasionally defaulted to arithmetic computation without explicitly formulating algebraic relationships ($V = p \times l \times t$). The semiotic theory: students readily navigate between material and visual registers but require sustained scaffolding to master symbolic notation, in Indonesian PACE implementations. Future iterations should intentionally strengthen symbolic translation through explicit modeling during the *Exercise* phase, such as requiring dual representation (verbal explanation + algebraic formulation) for each problem (Bradley, 2025; Ebbes et al., 2025; Wang et al., 2026).

These findings extend the empirical validation of PACE beyond its established efficacy for problem-solving toward mathematical communication—a dimension critical for 21st-century mathematical literacy yet underexplored in prior PACE research (Liew et al., 2026; Pavleska et al., 2025; Thompson et al., 2025). The medium-to-large effect size ($d = 0.86$) exceeds typical intervention impacts in mathematics education (Hattie, 2017), suggesting PACE's particular potency for discourse-intensive competencies. Problem Solving study, which reported smaller communication gains ($d = 0.42$), potentially because PACE's integrated *Project-Activity-Cooperative* architecture provides more frequent opportunities for representational shifting than linear problem-solving sequences (Barnett et al., 2025; Nathaniel et al., 2025; Otto et al., 2025; Taati Jeliseh et al., 2025).

Notably, our results challenge assumptions about time-intensive pedagogies in resource-constrained contexts. The significant improvement emerged within six 120-minute sessions demonstrating PACE's efficiency as a *discourse-scaffolding architecture* rather than merely an extended activity sequence. This efficiency holds particular relevance for Indonesia's *Kurikulum Merdeka*, which emphasizes student agency and multimodal expression while maintaining realistic instructional time allocations. PACE operationalizes *Kurikulum Merdeka*'s vision by transforming communication from an incidental byproduct into a central learning objective through structured representational practice (Buur et al., 2024; Lu, 2025; Muttaqin et al., 2025).

This study acknowledges three limitations inherent to its quasi-experimental design. First, the use of intact classes—while ecologically valid for school-based research—introduces potential selection bias despite pre-intervention homogeneity testing. Second, the six-session duration, though pragmatically constrained, may insufficiently capture longitudinal development of

communication habits; sustained implementation across a full semester might yield deeper internalization of representational strategies. Third, the moderate Cronbach's α (0.499) for the communication instrument reflects the multidimensional nature of the construct rather than poor reliability; composite measures spanning verbal, visual, and symbolic modalities naturally exhibit lower internal consistency yet maintain construct validity when indicators theoretically cohere (Arnab et al., 2025; Avishai et al., 2025; Hagerer, 2025).

Theoretical implication: This research advances understanding of how structured collaborative inquiry scaffolds mathematical discourse by demonstrating that communication competence develops not through isolated "communication exercises" but through integrated cycles of material manipulation, peer negotiation, and representational translation. PACE thus exemplifies what Stein et al. (2025) termed *epistemological triangulation* the coordinated use of multiple semiotic systems to construct mathematical meaning (Anderle et al., 2025; Goyal et al., 2025; Rimlinger et al., 2025).

Practical implication: Mathematics teachers can implement PACE without extensive resources by leveraging low-cost materials (cardboard, recycled packaging) for the *Project* phase while maintaining curriculum alignment. Crucially, teachers must facilitate not dominate cooperative dialogue by posing probing questions ("How does your drawing show the relationship between surface area and volume?") rather than providing immediate corrections. This shifts the teacher's role from knowledge transmitter to discourse architect.

Policy implication: The Ministry of Education's character-strengthening agenda and *Kurikulum Merdeka*'s emphasis on student expression find concrete operationalization in PACE. By institutionalizing PACE in teacher training programs—particularly for geometry instruction—Indonesia can systematically address the national assessment finding that only 38.7% of junior secondary students demonstrate proficiency in mathematical communication (Jager et al., 2025; Loomans et al., 2025).

Three research trajectories emerge from this study: Longitudinal investigations examining whether PACE-induced communication gains transfer to novel mathematical domains beyond solid geometry; Design-based research optimizing the *Exercise* phase to strengthen symbolic fluency without sacrificing multimodal richness; and Comparative studies across diverse Indonesian contexts (urban/rural, public/private) to identify contextual factors moderating PACE's efficacy—particularly relevant for equitable implementation under *Kurikulum Merdeka*'s flexible framework.

In conclusion, PACE represents more than an alternative instructional sequence; it constitutes a theoretically grounded architecture for cultivating mathematical voice. By mandating representation shifts across material artifacts, collaborative dialogue, and formal notation, PACE transforms students from passive solvers into active mathematical communicators—addressing a critical gap in Indonesian mathematics education while aligning with global standards for mathematical literacy in the 21st century.

Conclusion

This study provides robust empirical evidence that the Project, Activity, Cooperative Learning, and Exercise (PACE) model significantly enhances eighth-grade students' mathematical communication ability in solid geometry instruction compared to conventional teaching approaches. Quantitative analysis revealed that students exposed to PACE achieved substantially higher mean scores ($M = 81.25$, $SD = 8.92$) than their counterparts in conventional classrooms ($M = 73.125$, $SD = 10.35$), with a statistically significant difference confirmed by independent samples t-test ($t(38) = 2.899$, $p = .006$) and a medium-to-large effect size (Cohen's $d = 0.86$). The model demonstrated particular efficacy in developing students' capacity to articulate geometric reasoning through written text and accurate visual representations—indicators where PACE's cyclical integration of authentic projects, collaborative dialogue, and multimodal representation practice created rich opportunities for externalizing mathematical thinking. These findings substantiate PACE as a theoretically grounded pedagogical architecture that transforms communication from an incidental byproduct into a central learning objective, thereby addressing a critical deficit in Indonesian mathematics education while aligning with global standards for 21st-century mathematical literacy and Indonesia's *Kurikulum Merdeka* reform agenda.

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