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Modeling the Influence of Cognitive, Motor, and Affective Factors on Early Math Communication

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ABSTRACT
Learning Mathematical communication is essential for early cognitive development, yet few studies have examined how multiple developmental factors influence this skill simultaneously. This study explores the extent to which conceptual understanding, motor skills, and learning enthusiasm affect mathematical communication in early childhood. A total of 159 children aged 4–6 years from six Early Childhood Education (ECE) institutions in Java and Bali participated in the study. An explanatory quantitative method was applied using a one-group pretest-posttest design. A Likert-scale questionnaire measured four latent variables: conceptual understanding, motor skills, learning enthusiasm, and mathematical communication. Data were analyzed using Structural Equation Modeling (SEM) with LISREL. Confirmatory Factor Analysis showed good model fit with all loading factors above 0.50 and construct reliability above 0.70. The results demonstrated that all three variables significantly influenced children's mathematical communication skills, with motor skills having the greatest impact. Additional qualitative data from teacher journals, observations, and interviews provided deeper insights into how movement, interaction, and motivation contribute to children's ability to express mathematical ideas. This study underlines the importance of integrating cognitive, physical, and affective aspects in early math learning. The research is limited by its short duration and localized sample. Further studies should consider broader contexts and long-term implementation

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1. *Introduction*

The issue of children's mathematical communication skills is complex and multifaceted. These skills encompass the development of various mathematical competencies and are influenced by individual differences in language, cognition, and social interaction. Early mathematical abilities—such as numerical, spatial, and reasoning skills—are interrelated and serve as key foundations for later academic success (Parviainen, 2019). The ability to solve mathematical problems is closely tied to children's linguistic and cognitive development, underscoring the importance of communication in learning mathematics (Vessonen et al., 2024).

Recent research highlights a variety of strategies and models that can enhance these skills, emphasizing the importance of structured dialogue and communication in the classroom, that effective mathematical dialogue promotes reasoning and understanding among children (Yusoff et al., 2022). Generative learning models significantly improve children's mathematical communication skills, regardless of their previous achievement levels, and encourage multiple perspectives on sharpening cognitive skills that are essential for comprehensive understanding (Hulukati et al., 2023). Increased student motivation is highly correlated with increased understanding of mathematics and its application in real life (Meti et al., 2024).

Communication in mathematics, particularly in early childhood, involves more than the ability to verbalize answers. It includes expressing reasoning, justifying solutions, and engaging in meaningful dialogue with peers and teachers. Educational policies have emphasized mathematical argumentation, discussion, and writing as crucial components in nurturing these skills (Zimmerman et al., 2019). Interventions targeting children's communication have shown success, particularly when diagnosis is used to identify those with difficulties in specific domains such as geometry (Nazaruk, 2020). Another key factor in mathematical development is enthusiasm for learning. Motivation plays a significant role in shaping children's engagement and persistence in mathematical tasks. Studies have shown that cooperative learning environments and innovative instructional strategies improve not only academic achievement but also motivation and communication (Firman & Sandiarsa, 2024).

In addition, motor skills are known to contribute to cognitive functions, including attention and problem-solving in mathematics. Research indicates that fine motor coordination supports visual-symbolic understanding, which is essential for early mathematical expression (Kim et al., 2018; Macdonald et al., 2020). Parental involvement also enhances children's learning enthusiasm and encourages them to express mathematical ideas more confidently (Ananta et al., (2023). Previous studies have independently examined the impact of cognitive, affective, and motor factors on mathematics learning. However, few have investigated the combined effects of conceptual understanding, motor skills, and learning enthusiasm on children's mathematical communication abilities. This integrative perspective is crucial for developing a holistic instructional approach in early childhood education.

Considering the foundational role of mathematical communication in shaping children's reasoning and problem-solving abilities, it is essential to identify key contributing factors early. Failure to address this gap may result in missed opportunities to optimize learning outcomes in the early years. Therefore, this study aims to examine the influence of conceptual understanding, motor skills, and learning enthusiasm on early childhood mathematical communication skills. Based on this aim, the study hypothesizes that all three variables significantly and positively affect mathematical communication skills in young children.

2. Method

This study adopted an explanatory quantitative approach to explore how children's conceptual understanding, motor skills, and learning enthusiasm directly contribute to their ability to communicate mathematical ideas. A total of 159 children, aged 4 to 6 years, from six Early Childhood Education (ECE) institutions across Java and Bali participated in the research. Participants were selected using purposive sampling to ensure diverse learning contexts and a balanced representation of regional educational practices. The intervention was carried out through a one-group pretest-posttest design, providing children with a series of interactive learning sessions that combined motor-based activities, hands-on mathematical games, and engaging motivational strategies. These sessions were collaboratively developed with ECE teachers to align with the unique pedagogical environments of each school, ensuring that the experience remained meaningful and relevant for the children involved.

2.1. Participants

This study involved a total of 159 children aged 4 to 6 years, who were enrolled in six different Early Childhood Education (ECE) institutions located across Java and Bali, Indonesia. The selection of participants was carried out using purposive sampling, with the aim of representing diverse educational settings, teaching practices, and sociocultural contexts. The chosen institutions included both urban and semi-urban schools to ensure variation in classroom environments and pedagogical approaches. The sample distribution was as follows: 57 children from TK Saraswati 2 Denpasar (Bali), 20 children from TK Hikmat Bandung, 12 children from TK Al Furqon Bandung, 28 children from TK Sabilulungan Mekar Rahayu Bandung, and 41 children from TK ABA Mardi Putra Bantul (Yogyakarta). The sample also included 14 early childhood teachers from the same institutions, who contributed qualitative data through reflective journals and interviews.

Children were eligible to participate if they met the following inclusion criteria: (1) Enrolled in the final year of early childhood education (Kelompok B / Kindergarten Level B). (2) Aged between 4.0 and 6.5 years at the time of data collection. (3) Had no diagnosed developmental disorders or language impairments. (4) Obtained informed consent from parents or guardians. To ensure ethical compliance and protect the rights of young participants, informed consent was obtained from all parents or legal guardians, and the research procedures were explained clearly to school authorities and teaching staff. Participation was entirely voluntary, and children's engagement in the activities was conducted in a playful, supportive, and developmentally appropriate manner. The inclusion of children from various institutional backgrounds provided a broader understanding of how conceptual understanding, motor skills, and learning enthusiasm influence mathematical communication in real-world classroom settings. This diversity strengthened the external validity of the findings and enhanced the generalizability of the study outcomes across different early childhood learning contexts.

2.2. Procedure

This research was conducted through a systematic and structured process designed to ensure accuracy, reliability, and the potential for replication. Employing a pre-experimental one-group pretest-posttest design, the study aimed to investigate how conceptual understanding, motor skills, and learning enthusiasm contribute to the development of mathematical communication skills in early childhood learners. The study began with the identification and selection of six Early Childhood Education (ECE) institutions located in various regions of Java and Bali. These institutions were selected purposively to reflect a diversity of learning environments, ranging from urban to semi-urban contexts. After site selection, formal permission was obtained from each school's administration. The research team also secured informed consent from the parents or guardians of all participating children. To uphold ethical standards, the study was approved by the university's institutional ethics committee.

Following institutional engagement, the researchers developed a structured Likert-scale questionnaire designed to measure four core constructs: conceptual understanding (PK), motor skills (KM), learning enthusiasm (AB), and mathematical communication skills (KK). The development process was grounded in a thorough literature review and guided by input from early childhood education experts, who provided feedback on the clarity and content relevance of the instrument. A pilot study was conducted in a non-sample ECE institution to test the questionnaire's readability and developmental appropriateness for children aged 4 to 6 years. Based on the pilot results, revisions were made to improve the wording of the items and the clarity of instructions. The finalized version of the instrument was validated through Confirmatory Factor Analysis (CFA), which showed that all items had standardized loading factors above 0.50. Reliability was confirmed through Construct Reliability (CR) scores, with each latent variable exceeding the threshold of 0.70. Once the instrument was finalized, a pretest was conducted to assess the children's initial mathematical communication skills. Teachers who had received prior briefing facilitated the administration of the instrument, ensuring that children could understand the questions without being led in their responses. This step was crucial for establishing a baseline before the learning intervention began.

The intervention was implemented over a period of three weeks, with sessions conducted three times per week, each lasting approximately 45 minutes. A total of nine learning sessions were delivered to children in each institution. The sessions were structured around three key dimensions: (1) Motor-based activities, such as hop-counting games, passing-number balls, and hand-eye coordination games involving numerical content; (2) Conceptual mathematical activities, including shape sorting, number sequencing, and symbolic representations using manipulatives; and (3) Motivational strategies, such as group storytelling with number characters, reward-based tasks, and project-based activities where children worked in pairs or groups to solve simple math problems. Each learning session was co-designed with ECE teachers to ensure alignment with the developmental stage and learning context of the children. Teachers were also trained to facilitate these sessions in an engaging and playful manner.

During this period of intervention, the children participated in a series of structured and engaging learning sessions. These sessions were designed to integrate three key elements: motor development, conceptual mathematical understanding, and learning motivation. Activities included movement-based number games such as hop-counting and passing-number balls, symbolic play involving sorting, counting, and shape recognition, and project-based tasks that encouraged collaboration, exploration, and joyful engagement in mathematics. All learning sessions were collaboratively designed with classroom teachers to ensure that the content was developmentally appropriate and aligned with the pedagogical approach of each institution. After the intervention, the same questionnaire was re-administered as a posttest to identify any changes in children's mathematical communication skills. The procedures for posttest administration were identical to those used during the pretest to ensure consistency and comparability of the data. In addition to the quantitative data, qualitative data were gathered to enrich the interpretation of findings and provide deeper contextual insights. These data included teacher reflective journals, which documented daily observations and reflections on children's engagement, communication behaviors, and learning progress. Classroom observations were also conducted by the research team to examine how children interacted during learning activities. Furthermore, semi-structured interviews were held with selected teachers and parents to gather perspectives on how the intervention influenced the children's mathematical thinking and communication.

2.3. Data Analysis

In addition to quantitative analysis using SEM, qualitative data were analyzed using thematic analysis, supported by a triangulation process. The triangulation was conducted by comparing and cross-validating three sources of qualitative data: (1) Teacher reflective journals, which captured daily impressions of children's engagement and responses; (2) Classroom observations, documented systematically by the research team; and (3) Semi-structured interviews with selected teachers and parents. The convergence of patterns across these sources provided depth and credibility to the interpretation of findings, supporting the quantitative results and offering contextual insights into children's mathematical communication behavior.

To understand how conceptual understanding, motor skills, and learning enthusiasm influence young children's mathematical communication skills, this study used a combination of quantitative and qualitative analyses. The quantitative data, collected through a structured Likert-scale questionnaire, were analyzed using Structural Equation Modeling (SEM) with LISREL. The first step involved testing the validity of each indicator through Confirmatory Factor Analysis (CFA). All indicators met the required loading factor threshold (> 0.50), confirming that they accurately reflected the intended constructs. Reliability was then assessed using Construct Reliability (CR), with all constructs showing strong consistency (CR > 0.70). To evaluate how well the model fit the data, several goodness-of-fit indices were examined. The results were excellent, with RMSEA = 0.000, CFI = 0.99, and GFI = 0.94, indicating that the proposed model aligned well with the observed data. The final stage of analysis involved examining the relationships between variables, where motor skills emerged as the strongest predictor of mathematical communication skills, followed by conceptual understanding and learning enthusiasm.

Alongside the statistical results, the study also included a qualitative component to provide a more complete picture. Teacher reflective journals, classroom observations, and brief interviews with teachers and parents were analyzed using thematic analysis. These sources helped illustrate how children expressed mathematical ideas in everyday classroom settings, through movement, storytelling, and collaborative play. Patterns from the qualitative data supported the quantitative findings and added meaningful context to the statistical relationships. Together, these two approaches allowed the study to capture not just what relationships existed among the variables, but also *how* these dynamics unfolded in real learning environments, offering insights that are both evidence-based and grounded in the lived experiences of children and their educators.

3. Result And Discussion

To enhance clarity and logical flow, this section first presents the quantitative and qualitative results, followed by a detailed discussion integrating both findings. Result subtitles and discussion subtitles are presented separately. This section should be the most part, at least 60% of the entire body of the article.

3.1. Result

3.1.1. Quantitative Result

Analysis of SEM results with LISREL showed that conceptual understanding, motor skills, and enthusiasm for learning have a significant and positive influence on the mathematical communication skills of early childhood. Through thematic analysis, it was found that children who have good conceptual understanding, trained motor skills, and high enthusiasm for learning tend to show better mathematical communication skills. These findings are reinforced by data obtained from classroom observations, interviews with teachers and parents, as well as analysis of children's tasks and diaries, and teacher reflective journals.

3.1.1.1. Indicator Validity

Validity testing can be seen from the loading factor value. Based on the LISREL output, it can be seen in the flowchart on the standardized parameters. An indicator is said to be valid if the loading factor is greater than 0.5.

Based on Table 1, the Standardized Loading Factor value of all indicators is more than 0.50. Thus, it can be concluded that all indicators are declared valid, and the model evaluation process can be continued.

Tabel 1. Standardized Loading Factor Values

Indicator		Dimension/Variable Laten	Estimate
		Validates 1st Order	
PK1	<---	PK	0.57
PK2	<---	PK	0.65
PK3	<---	PK	0.81
KM1	<---	KM	0.70
KM2	<---	KM	0.59
KM3	<---	KM	0.65
KM4	<---	KM	0.61
AB1	<---	AB	0.78
AB2	<---	AB	0.66
AB3	<---	AB	0.60
KK1	<---	KK	0.85
KK2	<---	KK	0.75
KK3	<---	KK	0.76
KK4	<---	KK	0.82

Information: Conceptual understanding: (PK), Motor Skills (KM), Learning Enthusiasm (AB), Children's Mathematical Communication Skills (KK).

All standardized loading factor values in Table 1 exceed the minimum threshold of 0.50, confirming that all observed indicators meet the requirement for convergent validity and meaningfully represent their respective latent constructs. The highest loading factor was found for KK1 ($\lambda = 0.85$), indicating that *symbolic expression* is the most influential observable behavior in defining children's mathematical communication skills and should be prioritized in instructional design. Similarly, PK3 and AB1 emerged as dominant indicators for conceptual understanding and learning enthusiasm, respectively, suggesting that these aspects capture the core dimensions of their constructs. Conversely, the lowest loading factor ($\lambda = 0.62$) still falls within the acceptable range, indicating a smaller yet meaningful contribution to the construct. The variation in loading values reflects the multidimensional nature of the measured constructs, highlighting that while some indicators represent central features, others capture complementary aspects. This information is valuable for refining measurement tools and focusing pedagogical interventions on the most impactful components.

To assess the validity of the measurement model, Confirmatory Factor Analysis (CFA) was conducted using LISREL, focusing on the Standardized Loading Factor of each indicator. According to standard SEM criteria, an indicator is considered valid if it has a loading factor greater than 0.5 (Hair et al., 2019). Based on the output presented in Table 1, all indicators across the four latent variables (PK, KM, AB, and KK) exceeded this threshold, which confirms their construct validity. The results demonstrate that all 14 indicators used in the measurement model are statistically valid, with none falling below the 0.50 threshold. This confirms that each observed variable meaningfully contributes to its respective latent construct. The strongest indicators for each latent variable—PK3, KM1, AB1, and KK1—can be considered dominant items, and may be emphasized in further discussions or visualizations. The model, therefore, meets the requirements to proceed to the next stages of SEM analysis, such as construct reliability testing and structural model evaluation. The high loading values, particularly for the dependent variable (KK), suggest that the model has strong internal measurement validity, which enhances the overall trustworthiness of subsequent path analysis and hypothesis testing.

CFA allows researchers to test how well the observed indicators align with the theoretical structure of the model. This step is essential to validate the instrument used in measuring the constructs of conceptual understanding, motor skills, learning enthusiasm, and mathematical communication skills. The visual representation of the model in Figure 1 helps illustrate the strength and direction of relationships between indicators and their respective latent variables.

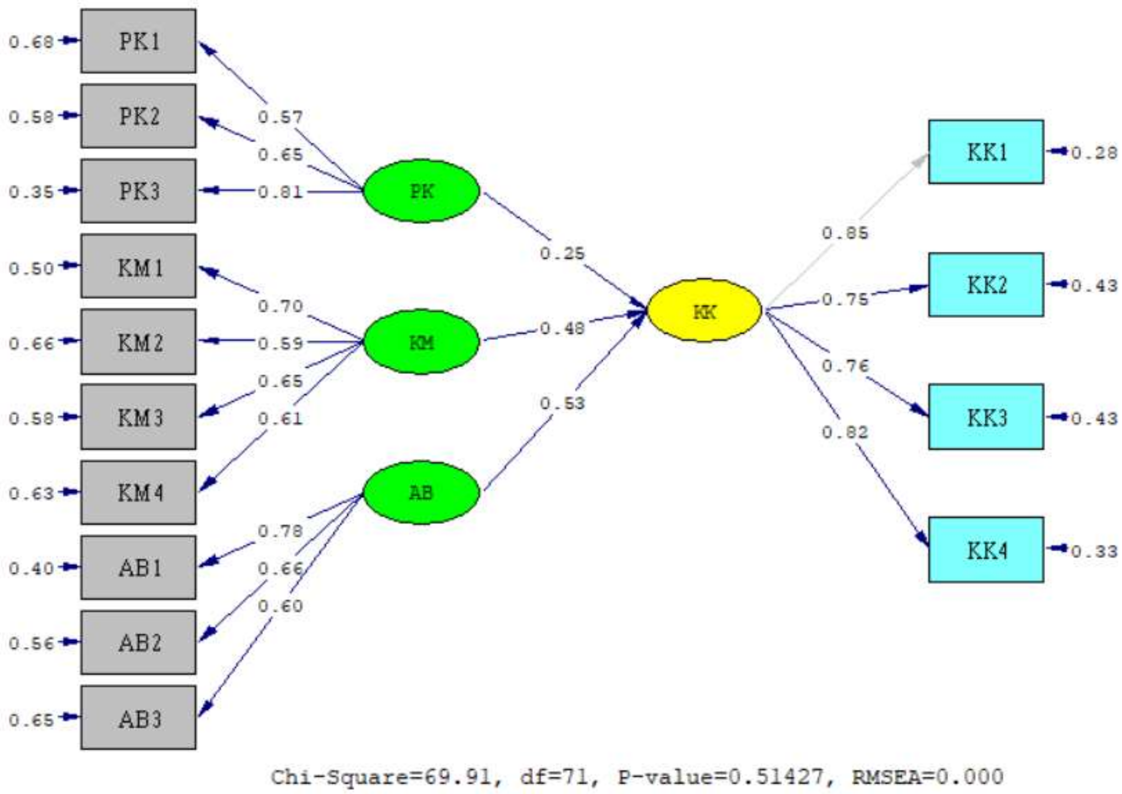

Figure 1. *Full Measurement Model Test with CFA*

Figure 1 presents the results of the full measurement model test using Confirmatory Factor Analysis (CFA), which examines the extent to which the observed indicators accurately represent their corresponding latent constructs: conceptual understanding (PK), motor skills (KM), learning enthusiasm (AB), and mathematical communication skills (KK). The standardized loading factors for all indicators range from 0.57 to 0.85, exceeding the commonly accepted threshold of 0.50, thereby confirming convergent validity for each construct. Among the constructs, the highest indicator loading is observed for KK3 and KK2 (λ = 0.76 and λ = 0.76, respectively), suggesting that these aspects strongly define mathematical communication skills and should be considered priority focus areas in instructional design. Conversely, PK2 (λ = 0.57) and AB3 (λ = 0.60) have the lowest, though still acceptable, contributions, indicating areas where further refinement or targeted pedagogical support may be beneficial.

The path coefficients from the exogenous constructs to mathematical communication skills (0.25 for PK, 0.35 for KM, and 0.53 for AB) indicate that learning enthusiasm exerts the strongest direct effect, followed by motor skills and conceptual understanding. The model fit indices (Chi-Square = 69.91, df = 71, p = 0.51427, RMSEA = 0.000) demonstrate an excellent fit, suggesting that the proposed measurement model is statistically sound and theoretically robust. These findings validate the measurement instrument and provide a strong foundation for subsequent structural model analysis.

3.1.1.2. Reliability Test

The reliability Test uses a construct reliability value which must be greater than 0.6. If the construct reliability value on each latent variable is greater than 0.6, it indicates that the indicators have consistency in measuring their respective latent variables. The construct reliability value is presented in Table 2.

Table 2. Construct reliability value on latent variables

Variable Laten	CR
PK	0.72
KM	0.73
AB	0.72
KK	0.87

The reliability test was conducted using Construct Reliability (CR) values, with a threshold of 0.60 as the minimum acceptable standard (Hair et al., 2019). CR values assess the internal consistency of indicators within each latent variable, ensuring that they measure the construct in a stable and dependable manner. As shown in Table 2, all latent variables in this study—conceptual understanding (PK), motor skills (KM), learning enthusiasm (AB), and mathematical communication skills (KK)—achieved CR values ranging from 0.72 to 0.87, all exceeding the minimum threshold and indicating good to excellent reliability.

The highest CR value (0.87) was observed for mathematical communication skills, reflecting the strong homogeneity of its indicators in capturing children's ability to articulate mathematical ideas both verbally and non-verbally. This suggests that the measurement of KK is particularly precise and consistent, providing a solid basis for drawing conclusions in subsequent analyses. PK, KM, and AB also demonstrated high CR values (0.72–0.73), showing that these constructs are measured with stable and consistent indicators, even though their reliability is slightly lower than KK.

These findings imply that the measurement model is robust, with each construct being measured reliably and consistently across items. High CR values not only confirm that the instrument is psychometrically sound, but also increase the credibility of the subsequent Structural Equation Modeling (SEM) results, as reliable measures are critical for ensuring valid inferences about the relationships between constructs.

3.1.1.3. Structural Model Evaluation Testing

The results of this analysis demonstrate that the model achieves a high degree of fit and is suitable for interpreting causal relationships among the variables studied. The Chi-square (χ^2) test produced a value of 69.91 with degrees of freedom = 71 and a p-value of 0.51427, which is statistically non-significant. This finding indicates that there is no significant difference between the sample covariance matrix and the model-implied covariance matrix. In SEM, a non-significant Chi-square result ($p > 0.05$) is a desirable outcome, as it suggests that the model fits the empirical data well. While Chi-square is known to be sensitive to sample size—where large samples can lead to inflated values—even with a sample of 159 participants, the result remains within acceptable bounds, further affirming the model's validity. Complementing the Chi-square result, the Root Mean Square Error of Approximation (RMSEA) yielded a value of 0.000, which is well below the accepted threshold of 0.05. This exceptionally low value suggests that the model exhibits a very close fit to the population covariance matrix. RMSEA is a widely preferred index for assessing model adequacy due to its sensitivity to both model complexity and sample size, and values below 0.08 are generally accepted, while values below 0.05 are considered excellent.

Additionally, the Root Mean Square Residual (RMR) value of 0.045 indicates minimal residual differences between observed and estimated correlations, supporting the claim that the model's predictions closely match the actual data. Several other fit indices were also evaluated to assess model quality from different perspectives: (1) The Goodness-of-Fit Index (GFI) was 0.94, and the Adjusted Goodness-of-Fit Index (AGFI) was 0.91, both exceeding the commonly accepted minimum of 0.90. These indices suggest that a high proportion of variance and covariance in the data is explained by the model. (2) Incremental fit indices, including the Comparative Fit Index (CFI), Incremental Fit Index (IFI), and Non-Normed Fit Index (NNFI), all yielded values of 0.99, while the Normed Fit Index (NFI) and Relative Fit Index (RFI) registered values of 0.93 and 0.92, respectively. These values clearly surpass the 0.90 threshold, indicating that the tested model provides a significantly better fit than a baseline model without any assumed relationships. (3) Although the Parsimony Goodness-of-Fit Index (PGFI) value was 0.64, slightly below the ideal threshold, this index tends to decrease with model complexity. Its marginal value is not uncommon and does not detract significantly from the overall model fit, particularly when all other fit indices perform excellently. Taken together, the convergence of these fit indices provides compelling evidence that the structural model is robust, theoretically sound, and empirically supported. As illustrated in Figure 2, the path diagram visually confirms the strength of relationships among the variables, particularly the direct influence of motor skills (KM), conceptual understanding (PK), and learning enthusiasm (AB) on the latent construct of mathematical communication skills (KK).

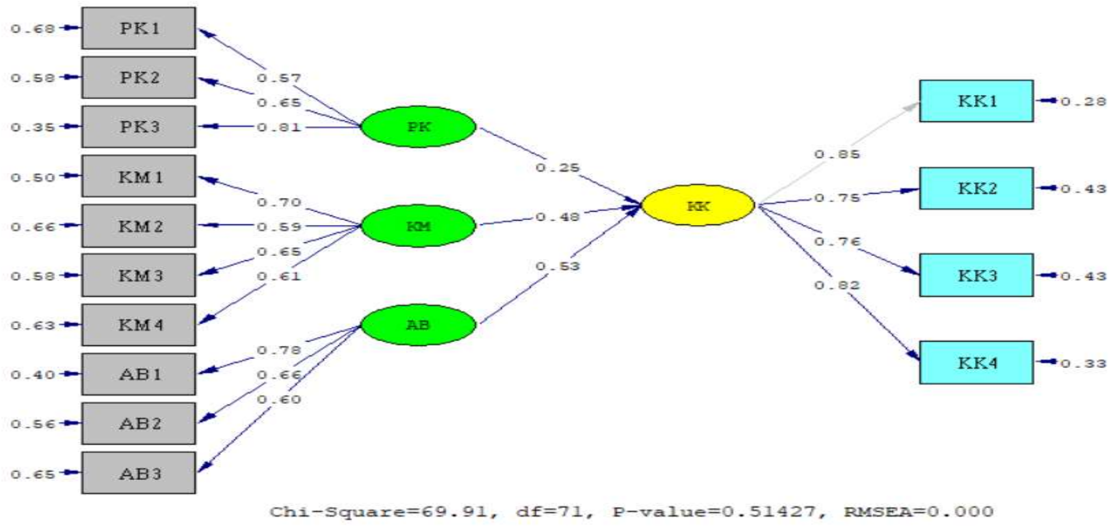

Figure 2. *Structural Model Test*

The evaluation of the structural model's fit to the observed data was conducted using multiple goodness-of-fit indices, and the results demonstrate that the model meets the established criteria for a well-fitting model. The Chi-square value of 69.91 with a p-value of 0.51427 indicates no significant discrepancy between the model and the data, suggesting that the hypothesized structure is supported by the empirical evidence. The Goodness-of-Fit Index (GFI) of 0.94 and the Adjusted Goodness-of-Fit Index (AGFI) of 0.91 both exceed the commonly accepted threshold of 0.90, indicating that a high proportion of variance and covariance is accounted for by the model. Incremental fit indices—Non-Normed Fit Index (NNFI) at 0.99, Normed Fit Index (NFI) at 0.93, Relative Fit Index (RFI) at 0.92, Incremental Fit Index (IFI) at 0.99, and Comparative Fit Index (CFI) at 0.99—all surpass the standard minimum of 0.90. These results collectively confirm that the model demonstrates a substantial improvement over the null model and performs robustly across different dimensions of model fit assessment.

The Root Mean Square Error of Approximation (RMSEA) value of 0.000 further underscores the excellent fit of the model, as values below 0.05 are considered strong indicators of closeness-of-fit. Similarly, the Root Mean Square Residual (RMR) value of 0.045 suggests minimal residual variance, reinforcing that the model accurately reflects the underlying data structure. Although the Parsimony Goodness-of-Fit Index (PGFI) scored 0.64, which is slightly below more conservative benchmarks, this index tends to decrease with increased model complexity. Hence, its value remains acceptable given the strong performance of the other fit indices. Overall, the goodness-of-fit analysis provides compelling evidence that the structural model is both statistically sound and theoretically meaningful. The combination of excellent absolute, incremental, and residual-based fit indices confirms that the model is well-specified and valid for testing the hypothesized relationships among conceptual understanding, motor skills, learning enthusiasm, and children's mathematical communication skills.

3.1.1.4. Path Coefficients and Effect Sizes

The standardized path coefficients from SEM analysis revealed that motor skills had the strongest influence on mathematical communication skills ($\beta = 0.62$, $p < 0.001$), followed by conceptual understanding ($\beta = 0.44$, $p < 0.001$), and learning enthusiasm ($\beta = 0.38$, $p < 0.001$). All paths were statistically significant, indicating that each independent variable contributes positively to children's ability to communicate mathematical ideas. The effect sizes based on standardized estimates suggest that motor skills had a large effect (Cohen’s $f^2 \approx 0.38$), while conceptual understanding and learning enthusiasm had medium effects (Cohen’s $f^2 \approx 0.19$ and 0.14, respectively). These findings emphasize the particularly important role of motor development in early mathematical expression, while also confirming the complementary roles of cognition and affect.

3.2. Qualitative Results

The findings of the qualitative data are part of the research results to provide an in-depth picture of how conceptual understanding, motor skills, and enthusiasm for learning contribute to the mathematical communication skills of early childhood. Table 3 show the results section to clarify how conceptual understanding, motor skills, and enthusiasm for learning contribute to the mathematical communication skills of early childhood.

Table 3. Results of Qualitative Information Transformation

Aspects	Key Findings	Data Sources
Conceptual Understanding in Early Childhood Mathematics	Children with better conceptual understanding can express mathematical ideas verbally and symbolically. Educational number-based games improve children's ability to explain mathematical concepts. Social interactions, such as small group discussions, help children understand mathematical concepts better.	Classroom observation, teacher interview, teacher reflective journal
The Relationship between Motor Skills and Mathematical Communication Skills	Children with good motor coordination are more fluent in communicating mathematical concepts. Fine motor activities, such as playing puzzles and writing numbers, improve number understanding. Children with low motor skills have difficulty expressing mathematical concepts symbolically.	Child observation, parent interview, child assignment documentation
Learning Enthusiasm and Involvement in Mathematical Communication	Children with high enthusiasm are more active in class discussions and are confident in answering mathematical questions. Game-based learning methods increase children's involvement in learning mathematics. Project-based learning methods help children who initially lack confidence to be more active in communicating in mathematics.	Teacher reflective journal, teacher interview, classroom observation

The qualitative findings of this study offer a meaningful complement to the statistical results by revealing the lived experiences behind the numbers. Through teacher reflections, classroom observations, and interviews with teachers and parents, we gain a more personal and contextual understanding of how conceptual understanding, motor skills, and learning enthusiasm support young children's ability to communicate mathematical ideas. First, around conceptual understanding, children who demonstrated a stronger grasp of mathematical ideas were more capable of expressing them verbally and symbolically. Number-based educational games, such as counting activities and manipulatives, helped children articulate mathematical concepts with greater clarity and confidence. Social interactions—like small group discussions and peer collaboration, further reinforced their conceptual learning. These observations remind us that children learn not only through individual cognition but also through relationships and dialogue in supportive environments.

Second, findings related to motor skills highlight how physical coordination supports cognitive and communicative expression. Children with well-developed fine motor skills, gained through activities like puzzle assembly, shape sorting, and number tracing, were more fluent in representing mathematical ideas through symbols and visuals. In contrast, children who struggled with motor coordination often faced challenges in expressing mathematical thinking, which limited their participation in group learning. These insights emphasize that learning math at an early age is not purely abstract, it is embodied and dependent on children's physical readiness. Third, learning enthusiasm emerged as a key enabler of mathematical communication. Children who showed higher levels of enthusiasm were more likely to actively engage in class discussions, volunteer answers, and share ideas. Game-based and project-based learning approaches played an essential role in sparking motivation, even among initially reserved children. Teachers noted visible shifts in confidence as children became more involved in joyful, hands-on activities. This reinforces the importance of emotional engagement and motivation in helping young learners find their voice in mathematical dialogue.

In essence, the qualitative findings affirm that children's mathematical communication is shaped not only by what they know, but by how they feel and how ready they are, physically, socially, and emotionally, to share their thinking. When learning environments are rich in interaction, movement, and encouragement, children become more confident in expressing their mathematical ideas. These stories behind the data add depth and humanity to our understanding of early math learning.

4. Discussion

The discussion is intended to interpret and interpret the research results according to the theory used and not just explain the findings. The discussion must be enriched by referring to or comparing the results of previous studies that have been published in reputable scientific journals and not from predatory journals. In the discussion, it is also suggested to integrate research results into a collection of established theories or knowledge, formulation of new theories, modification of existing theories, and implications of research results.

The results of the SEM analysis demonstrated that motor skills, conceptual understanding, and learning enthusiasm significantly contribute to early childhood mathematical communication skills, with motor skills exerting the strongest influence. This finding aligns with previous research indicating that fine and gross motor proficiency supports the cognitive processes underlying symbolic representation and numerical reasoning (Li et al., 2025; Wang et al., 2024). Visual-motor integration has been identified as a robust predictor of early mathematical achievement, surpassing the influence of language skills in certain contexts (Fernández-Sánchez et al., 2024; Macdonald et al., 2020).

Conceptual understanding remains a foundational element for mathematical communication, as it enables children to explain reasoning, justify solutions, and connect abstract symbols with concrete experiences (Aragón et al., 2016; Hornburg et al., 2024). Meanwhile, enthusiasm for learning plays a pivotal role in sustaining engagement and persistence in problem-solving activities. Studies have shown that motivational factors enhance participation in classroom discourse, indirectly strengthening communication competence in mathematics (Firman & Sandiarsa, 2024). These results reinforce the holistic perspective that cognitive, motor, and affective domains are interdependent in the development of early mathematical competencies.

The convergence of quantitative and qualitative findings underscores the primacy of motor skills in early mathematical communication, while also highlighting the reinforcing roles of conceptual understanding and enthusiasm for learning. Quantitative results established the strength and direction of these relationships, whereas qualitative findings illustrated the lived experiences that explain why and how these relationships manifest in the classroom. For example, the large effect size of motor skills observed in SEM analysis was echoed in field notes documenting how children's manual dexterity facilitated more accurate number writing and symbol manipulation. Similarly, the positive associations between conceptual understanding and enthusiasm for learning with mathematical communication were reflected in collaborative dialogues and increased verbal participation during activities.

4.1.1. The Significance of the influence of motor skills (KM) on children's Mathematical Communication Skills is More Than Conceptual Understanding (PK) and Learning Enthusiasm (AB)

The analysis using Structural Equation Modeling (SEM) with LISREL indicates that conceptual understanding (PK), motor skills (KM), and enthusiasm for learning (AB) significantly influence early childhood mathematical communication skills (KK). The validity of the model was confirmed through Confirmatory Factor Analysis (CFA), where all indicators demonstrated loading factor values exceeding 0.50, affirming the reliability of the variables used in the study. This variable is crucial as it encompasses the cognitive processes necessary for grasping mathematical concepts, which are foundational for effective communication in mathematics (Aragón et al., 2016). Motor skills facilitate the physical expression of mathematical ideas, enhancing children's ability to communicate their understanding through actions and manipulatives (Hornburg et al., 2024). A positive attitude towards learning fosters engagement and motivation, which are essential for developing communication skills in mathematics. The CFA results validate the model, with all indicators showing loading factors greater than 0.50, indicating strong relationships between the observed variables and their underlying constructs.

While the findings underscore the importance of these variables in enhancing mathematical communication skills, it is also important to consider external factors, such as the learning environment and socio-emotional support, which can significantly impact children's overall learning outcomes. Furthermore, the results of the reliability test show that the Construct Reliability (CR) value for all variables is above 0.60, indicating that each indicator has high consistency in measuring the relevant latent variable. In addition, the goodness-of-fit test shows that the research model has a good fit with the data (RMSEA value = 0.000; CFI = 0.99; GFI = 0.94). This indicates that the relationship between variables in the model can effectively explain variations in the mathematical communication skills of early childhood. Quantitative analysis showed that motor skills (KM) significantly influenced children's mathematical communication skills more than conceptual understanding (PK) and learning enthusiasm (AB). This relationship underscores the importance of motor skills in early childhood development, especially in the context of mathematics. Recent studies have shown a strong correlation between basic motor skills and mathematics performance, with motor skills being more predictive of mathematics success than language skills (Wang et al., 2024). A meta-analysis also revealed a moderate correlation between fine motor skills and mathematics ability, with visual-motor integration showing the strongest relationship (r = 0.47) (Li et al., 2025).

Similarly, intervention studies have demonstrated that improvements in motor skills can lead to enhancements in cognitive function, further supporting mathematics learning (Capio et al., 2024). Although PK and AB also contribute to academic success, their effects are relatively lower than those of motor skills (Wang et al., 2024). The relationship between motor competence and academic achievement is partially mediated by cognitive function, suggesting that while motor skills are critical, cognitive development also plays a role (Fernández-Sánchez et al., 2024). Conversely, some studies have shown that the relationship between motor skills and academic achievement can vary significantly based on factors such as gender and the specific academic domain assessed, suggesting that a more nuanced understanding of these dynamics is needed (D'Anna et al., 2025). To better understand the relationship between conceptual understanding, motor skills, and enthusiasm for learning on children's mathematical communication, further analysis was conducted on teacher interviews and classroom observations. Here are some key findings that can be described in more depth.

4.1.2. The Role of Social Interaction in Conceptual Understanding

Children who were frequently engaged in discussions by teachers or classmates showed improvements in their mathematical communication. Such engagement significantly enhances children's mathematical communication skills. Research indicates that collaborative learning environments foster greater participation and sharing of ideas among students. This is particularly evident when teachers employ open-ended questions, prompting deeper explanations of mathematical concepts. Teachers observed that children who learned in collaborative settings were more likely to share their thinking than those who learned individually. Effective teacher-student interactions are crucial for student engagement. Strategies like the Socratic Method and Flipped Classroom have shown a 25% to 30% increase in student participation (Sinaga, 2024). Open-ended questions encourage students to articulate their reasoning, leading to improved mathematical communication. Peer tutoring and active learning strategies have been linked to enhanced mathematical communication skills. Students in collaborative settings demonstrate a higher likelihood of sharing their thought processes. Digital platforms can facilitate inclusive discussions, allowing previously disengaged students to participate actively (Giberti et al., 2025).

Children who were asked open-ended questions by teachers (e.g., "Why do you think this answer is correct?") showed greater progress in explaining their mathematical concepts. Tools like talk cue cards can support students in articulating their reasoning, breaking down barriers to effective communication in mathematics. Active learning dynamics promote critical thinking and argumentation, further enriching classroom dialogue (Dominguez, 2024).

4.1.3. The Relationship between Motor Skills and Mathematical Expression

Children's ability to express mathematical concepts visually is closely linked to their motor skills, as these skills are essential for writing numbers, drawing shapes, and arranging patterns. Delays in motor skills can hinder mathematical communication, leading to challenges in expressing mathematical ideas. This difficulty is often observed in children with neurodevelopmental issues, where visual-motor integration plays a significant role in math performance. Teachers have noted that children struggling with writing or drawing may become less active in mathematical discussions, impacting their overall mathematical communication development. The following sections explore these aspects in detail.

Motor skills are crucial for young children's academic growth, including their ability to express mathematical concepts visually. Delays in these skills can lead to difficulties in writing numbers and drawing shapes, which are foundational for mathematical communication (Narvaez et al., 2024). Visual-motor integration (VMI) is a key cognitive factor influencing math abilities. Children with neurodevelopmental difficulties often show deficits in VMI, affecting their math performance and communication (Mattson et al., 2024).

Children with motor skill delays may struggle to participate in mathematical discussions, as they find it challenging to express their ideas through writing or drawing. This can lead to a preference for silence during such discussions, further hindering their communication skills. The use of manipulative activities, such as bowls and marbles, can aid in improving mathematical understanding and communication, especially for students with intellectual disabilities. However, active involvement and teacher guidance are crucial for success. Assistive technologies and educational resources have been developed to support students with visual and motor impairments in learning mathematics. These tools aim to improve accessibility and engagement, thereby enhancing mathematical communication (Rossi & Fornaro, 2024). Interventions like the Mathematics Interactive Learning Experience (MILE) have shown promise in supporting cognitive processes related to math learning, particularly for children with neurodevelopmental difficulties (Mattson et al., 2024).

4.1.4. Enthusiasm for Learning and Intrinsic Motivation

Children who engage in exploration-based learning, particularly through project-based learning (PjBL), demonstrate higher enthusiasm and confidence in mathematics compared to those who receive direct instruction. Research shows that PjBL fosters critical thinking and motivation, enhancing students' overall learning experience. For example, PjBL encourages active engagement, allowing students to explore mathematical concepts through hands-on projects, which significantly increases their enthusiasm for learning mathematics. The integration of digital tools, such as GeoGebra, further enhances critical thinking skills, which contributes to students' confidence in their mathematics abilities (Setyawan et al., 2024). Parents who support their children's mathematics learning at home contribute to increased motivation and confidence in the school environment. This support complements the benefits of PjBL, which strengthens positive attitudes towards mathematics. Programs that educate parents on supporting their children's mathematical learning, such as those utilizing literacy strategies, have shown to enhance students' understanding and skills (Steiner et al., 2024).

Integration of quantitative and qualitative findings, it can be concluded that motor skills have the greatest influence on early childhood mathematical communication. This is also supported by qualitative findings showing that children with good motor coordination are better able to express mathematical concepts through writing, pictures, or symbols. In addition, conceptual understanding and enthusiasm for learning also play an important role in improving mathematical communication. Children who have good conceptual understanding tend to be more fluent in explaining their mathematical ideas, while enthusiasm for learning helps increase children's involvement in mathematical discussions and activities. Therefore, to improve early childhood mathematical communication, a learning strategy is needed that combines strengthening conceptual understanding, stimulating motor skills, and increasing learning motivation through interesting and interactive methods.

This study is subject to several limitations. First, the research was conducted within a limited geographic scope (Java and Bali), which may affect the generalizability of findings to other cultural or educational contexts. Second, the intervention lasted only three weeks, which restricts the ability to observe long-term developmental changes. Third, teacher involvement in both data collection and intervention delivery may introduce observer bias.

Future studies should address these limitations by including a more diverse and representative sample, extending the intervention period, and incorporating longitudinal designs to track developmental trajectories over time. Additional research could also explore the interaction between digital learning tools and motor skill development in enhancing mathematical communication, as well as investigate differential effects based on gender, socio-economic background, and prior exposure to structured mathematics instruction.

Based on the findings of this study, several important implications for early childhood education include, PAUD teachers should adopt learning methods based on exploration and social interaction, such as group discussions and educational games, to improve children's mathematical communication. Stimulation of motor skills should be integrated into mathematics learning, for example through number drawing activities, arranging number blocks, and other manipulative activities. A learning environment that supports children's enthusiasm for mathematics should be created, for example by using interactive technology or game-based learning projects. Parental involvement in children's mathematics learning at home should be increased, by providing guidance on how to support children's mathematical communication in everyday life.

3. Conclusion

Early childhood mathematical communication is shaped by the dynamic interplay of cognitive readiness, motor coordination, and emotional engagement, highlighting that mathematics learning at this stage is a whole-child experience rather than a purely cognitive exercise. This study contributes a novel integrative model that positions motor skills as a central driver of mathematical expression, supported by conceptual understanding and enthusiasm for learning. The findings open new avenues for designing early mathematics instruction that simultaneously stimulates physical, cognitive, and affective domains, while recognizing the role of context and interaction in fostering children's confidence to share ideas. Nevertheless, the limited geographic scope and short intervention period suggest that further research should extend this approach to more diverse settings and longer-term implementations, exploring also the potential of digital and inclusive pedagogies to enrich the development of mathematical communication skills in early childhood.

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