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Embodied Interaction, Spatial Language, and Mathematical Communication: The Moderating Role of Classroom Engagement

Emmanuel Kusi

University of Skills Training and Entrepreneurial Development, Ghana

<https://orcid.org/0009-0000-3757-0005>

Yarhands Arthur Dissour

University of Skills Training and Entrepreneurial Development, Ghana.

<https://orcid.org/0000-0002-8950-1367>

Francis Ohene Boateng

University of Skills Training and Entrepreneurial Development, Ghana.

<https://orcid.org/0000-0003-0197-7385>

Stephen Daniels Sarfo

University of Skills Training and Entrepreneurial Development, Ghana

<https://orcid.org/0009-0000-8305-6947>

Innocent Akpage

University of Skills Training and Entrepreneurial Development, Ghana

<https://orcid.org/0009-0001-8526-6806>

ABSTRACT

Mathematical communication is essential for effective mathematics learning, yet many students struggle to communicate mathematical ideas. Grounded in Embodied Cognition Theory, Conceptual Metaphor Theory, and the 4E Cognition Framework, this study examined the influence of embodied interaction on mathematical communication among Ghanaian SHS students, with spatial

language as a mediator and classroom engagement as a moderator. A cross-sectional survey was conducted with 420 SHS 2 and SHS 3 students selected through multistage sampling. Data were analysed using SEM. Embodied interaction significantly predicted mathematical communication ($\beta = .321$, $p < .001$). Spatial language partially mediated the relationship (indirect effect = .209, 95% BC CI [.114, .293]), whereas classroom engagement did not significantly moderate it ($\beta = .055$, $p = .131$).

Keywords: Classroom engagement, embodied interaction, mathematical communication, spatial language

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INTRODUCTION

Mathematical communication is widely recognized as a fundamental component of mathematics learning and achievement in the twenty-first century (Johar et al., 2025; Mujiasih et al., 2021). Beyond obtaining correct answers, students are expected to explain their reasoning, justify procedures, interpret mathematical representations, and communicate ideas using appropriate mathematical language and symbols (NCTM, 2014; OECD, 2023). Effective mathematical communication promotes conceptual understanding, mathematical reasoning, argumentation, and collaborative problem-solving (Bicer et al., 2020; Patel & Pfannkuch, 2018; Planas, 2021; Sfard, 2021). Despite its importance, many students struggle to express mathematical ideas clearly, particularly when dealing with abstract and spatially demanding concepts (Hawes & Ansari, 2020; Xu et al., 2025). These difficulties are often more pronounced in developing educational contexts where instruction tends to prioritize procedural competence over conceptual understanding and communication (Asare, 2024; Fokuo et al., 2022).

Recent developments in mathematics education have increasingly emphasized embodied approaches to learning, highlighting the role of bodily actions, gestures, movement, and interaction with physical or digital objects in mathematical thinking (Abrahamson & Lindgren, 2014; Alibali & Nathan, 2012). Grounded in Embodied Cognition Theory, these approaches suggest that mathematical understanding emerges through sensory and motor experiences

rather than solely through abstract mental processes (Newen et al., 2018; Wilson & Golonka, 2013). Embodied interaction, which involves learners' active engagement with mathematical ideas through movement, gestures, and object manipulation, has been shown to enhance conceptual understanding, problem-solving, and mathematical expression (Abrahamson et al., 2020; Kersey et al., 2024). Consequently, embodied interaction has emerged as a promising pedagogical approach for improving mathematical communication (Boonstra et al., 2023; Chatain et al., 2024; Way & Ginns, 2024).

One mechanism through which embodied interaction may influence mathematical communication is spatial language. Spatial language refers to words and expressions used to describe location, direction, movement, orientation, shape, and spatial relationships (Bower et al., 2020; Turan & De Smedt, 2023). It plays a critical role in organizing and communicating mathematical ideas, particularly in geometry, measurement, and spatial reasoning (Atit et al., 2022a). Conceptual Metaphor Theory suggests that abstract mathematical concepts are often understood through language grounded in bodily and spatial experiences (Shute, 2005). Through embodied activities, learners develop spatial vocabulary that enables them to communicate mathematical relationships more effectively. Consistent with this view, studies have linked strong spatial language skills to higher levels of mathematical understanding, reasoning, and communication (Atit et al., 2022b; Bufasi et al., 2024). However, limited research has examined spatial language as a mechanism through which embodied interaction influences mathematical communication, particularly among secondary school students in Sub-Saharan Africa.

Classroom engagement may also shape the effectiveness of embodied learning experiences. Engagement reflects students' behavioral participation, cognitive investment, and emotional involvement in learning activities (Bond et al., 2020; Fredricks, 2023). According to the 4E Cognition Framework, learning emerges through interactions between learners and their physical and social environments (Newen et al., 2018). Learners who actively participate in embodied mathematical activities may therefore be better able to translate physical experiences into meaningful mathematical communication (Abrahamson et al., 2020; Abrahamson et al., 2025). Although classroom engagement may strengthen or weaken the influence of embodied interaction on mathematical communication, empirical evidence regarding this moderating role remains limited (Smith, 2024; Zhou et al., 2024).

Despite growing interest in embodiment, spatial language, and engagement in mathematics education, important gaps remain. Most existing studies have been conducted in North America, Europe, and East Asia, with relatively little evidence from Sub-Saharan Africa (Atit et al., 2022; Hawes et al., 2024). Within African contexts, research has focused largely on achievement, attitudes, anxiety, and instructional strategies, with limited attention to the cognitive and linguistic

processes underlying mathematical communication (Asare, 2024; Fokuo et al., 2022; Tabiri et al., 2025). Moreover, studies on embodied learning have predominantly examined direct effects on achievement and conceptual understanding, often overlooking the mediating role of spatial language and the contextual influence of classroom engagement (Abrahamson et al., 2020; Nathan, 2021). Building on the foregoing discussion, this study examines the influence of embodied interaction on mathematical communication among Senior High School students in Ghana. Specifically, it investigates whether spatial language mediates the relationship between embodied interaction and mathematical communication and whether classroom engagement moderates this relationship. Accordingly, the study tests three hypotheses concerning the direct, mediating, and moderating relationships among these constructs.

Problem Statement

Although embodied approaches have increasingly been recognised as promising for mathematics learning, little is known about the mechanisms through which embodied interaction enhances students' mathematical communication, particularly within Sub-Saharan African contexts.

Spatial language may represent one such mechanism. Research has consistently linked spatial language to mathematical reasoning, geometry learning, and spatial thinking (Atit et al., 2022; Pruden et al., 2021; Verdine et al., 2017; Zhang et al., 2024). Although embodied cognition perspectives propose that bodily experiences are translated into linguistic representations that facilitate mathematical thinking and communication (Lakoff & Núñez, 2000; Nathan, 2021), empirical evidence examining spatial language as a mediating pathway between embodied interaction and mathematical communication remains limited.

Classroom engagement may also influence the effectiveness of embodied learning experiences. Although engagement has consistently been associated with active participation and positive learning outcomes (Bond et al., 2020; Fredricks et al., 2023; Kahu & Nelson, 2018). Yet, little is known about whether classroom engagement strengthens or weakens the relationship between embodied interaction and mathematical communication (Abrahamson et al., 2023). This limit understanding of the conditions under which embodied instructional practices are most effective (Nathan et al., 2021). These gaps are particularly evident in Ghana, where mathematics education research has largely focused on achievement, attitudes, instructional strategies, anxiety, and technology integration (Asare, 2024; Fokuo et al., 2022; Tabiri et al., 2025). Comparatively little attention has been given to how embodied interaction, spatial language, and classroom engagement jointly contribute to students' mathematical communication. Moreover, existing studies have typically examined these variables in isolation

rather than within an integrated framework capable of capturing direct, indirect, and conditional effects simultaneously.

Accordingly, this study examines the direct effect of embodied interaction on mathematical communication, the mediating role of spatial language, and the moderating role of classroom engagement within an integrated structural model among Senior High School students in Ghana.

Objectives

1. To examine the effect of embodied interaction on mathematics communication.
2. To examine the mediating role of spatial language in the nexus of embodied interaction and mathematical communication.
3. To assess the moderating role of classroom engagement in the relationship between embodied interaction and mathematical communication.

Significance

This study contributes to the literature on embodied mathematics learning by examining the roles of spatial language and classroom engagement in explaining mathematical communication among senior high school students in Ghana. The findings provide empirical evidence to inform mathematics instruction by highlighting the importance of embodied learning experiences and the development of spatial language in enhancing students' mathematical communication. The findings may also inform teacher education programmes by highlighting the importance of preparing prospective mathematics teachers to incorporate embodied instructional strategies and spatial language into classroom practice.

LITERATURE REVIEW

This section synthesizes the existing literature across three major thematic areas: embodied interaction and mathematical communication, spatial language as a mediating mechanism, and classroom engagement as a moderating factor.

Embodied Interaction and Mathematical Communication

Embodied interaction has gained increasing attention in mathematics education because learning is shaped by bodily experiences and interactions with the environment. Grounded in Embodied Cognition Theory, it involves the use of gestures, bodily movement, object manipulation, and sensory experiences to support mathematical thinking (Barsalou, 2016; Wilson & Golonka, 2013). From this perspective, mathematical understanding develops through active engagement

with physical and symbolic representations rather than through abstract reasoning alone.

However, the literature is not fully consistent in how it positions the role of the body in this process. Some accounts treat gesture and movement as constitutive of mathematical understanding itself, meaning the physical action is where the thinking happens, not merely an aid to it (Abrahamson et al., 2020). Other accounts treat embodied action primarily as a communicative channel, a means through which an already-forming understanding is externalized and refined through interaction with others (Alibali et al., 2023; Walkington et al., 2019). These are not equivalent claims: the first implies embodiment shapes what students come to understand, while the second implies embodiment mainly shapes how well students can express what they already understand.

Most studies do not distinguish between these mechanisms, which makes it difficult to know whether embodied interaction is expected to improve mathematical communication by deepening conceptual understanding, by providing students with a richer expressive repertoire, or both. A further limitation is that the empirical base for this literature is drawn overwhelmingly from studies of conceptual understanding, reasoning, and problem-solving as outcomes (Abrahamson et al., 2020; Alibali et al., 2023; Walkington et al., 2019); comparatively few studies isolate mathematical communication (explaining, justifying, interpreting representations, and engaging in discourse (Moschkovich, 2018; Sfard, 2021) as the outcome of interest in its own right.

It therefore remains unclear whether the well-documented benefits of embodied interaction for conceptual learning extend, with the same strength, to students' capacity to communicate mathematical ideas. This gap is what the present study addresses by treating mathematical communication as the primary outcome rather than a secondary correlate of conceptual gains. Based on the reviewed literature, the researchers hypothesize that:

H1: Embodied interaction has a significant positive effect on mathematical communication.

Spatial Language as a Mediator

Spatial language refers to the words and expressions used to describe location, direction, orientation, movement, distance, and spatial relationships among objects (Pruden et al., 2021). It is increasingly recognized as an important cognitive and linguistic resource that supports mathematical thinking and communication. According to Conceptual Metaphor Theory, abstract mathematical concepts are often understood and communicated through spatial representations grounded in bodily experiences (Lakoff & Núñez, 2000). As a result, spatial language may

serve as a mechanism through which embodied experiences are translated into mathematical communication.

The empirical support for this pathway, however, is drawn from a narrower evidence base than it first appears. Much of the work linking embodied or interactive experience to spatial language development comes from early-childhood and primary-grade populations. For example, Ren et al. (2022) examined spatial language during parent-child play with first graders, while the broader spatial-skills-and-mathematics literature spans a wide age range without consistently testing whether the same linguistic mechanism operates in adolescence (Atit et al., 2022; Verdine et al., 2017). Conceptual Metaphor Theory itself was developed primarily through cognitive-linguistic analysis of abstract reasoning rather than through classroom-based instructional research (Lakoff & Núñez, 2000), so its extension to a secondary school instructional setting remains a theoretical inference rather than a tested claim

This creates a genuine inconsistency for the present study to resolve: is spatial language a mechanism that operates similarly across development, or is it a primarily early-developmental pathway whose relevance to older adolescents' mathematical communication has simply not been tested? Because SHS students in Ghana are considerably older than the samples in most of the foundational spatial-language studies, and because prior work has rarely traced this pathway as a formal mediating mechanism between embodied interaction and communication specifically (rather than achievement or reasoning more broadly), it is unclear whether the mediating role documented in younger, largely Western samples generalizes to this population and context. Testing spatial language as an explicit mediator in an adolescent Sub-Saharan African sample is the specific contribution of this study, not simply a geographic extension of existing findings. Accordingly, this study proposes:

H2: Spatial language significantly mediates the relationship between embodied interaction and mathematical communication.

Classroom Engagement as a Moderator

Classroom engagement is a key determinant of effective learning and academic success. It reflects students' behavioral participation, cognitive investment, and emotional involvement in classroom activities (Fredricks et al., 2023). Engaged learners are more likely to participate in discussions, collaborate with peers, persist in challenging tasks, and communicate their ideas effectively.

Research consistently links engagement to positive educational outcomes. Highly engaged students demonstrate stronger learning outcomes, greater participation in classroom discourse, and increased willingness to express ideas and engage in collaborative problem-solving (Bond et al., 2020; Kahu & Nelson,

2018; Sinatra et al., 2015). Yet the literature offers two competing accounts of how engagement operates that carry different implications for the present model. One view, consistent with the 4E Cognition Framework, treats engagement as a condition that shapes the effectiveness of other learning processes; in this framing, embodied interaction and engagement interact, such that the benefits of embodied activity depend on how engaged the learner already is (Newen et al., 2018). A second view, articulated by Kahu and Nelson (2018) among others, treats engagement as functioning primarily as a direct, independent predictor of learning outcomes rather than as a variable that conditions the effect of other instructional processes. These two positions are not simply complementary; they generate different empirical predictions. The first predicts a significant interaction between embodied interaction and engagement; the second predicts that engagement and embodied interaction would each contribute independently, with no interaction term reaching significance. Existing studies have rarely tested these accounts against each other directly in the context of embodied mathematics instruction, and moderation of embodied interaction’s effects by classroom engagement has not, to our knowledge, been empirically examined at all in this literature. The present study therefore treats classroom engagement’s moderating role as an open empirical question rather than a settled expectation, and tests it directly. Based on the reviewed literature, the researchers posit that:

H3: Classroom engagement significantly moderates the relationship between embodied interaction and mathematical communication.

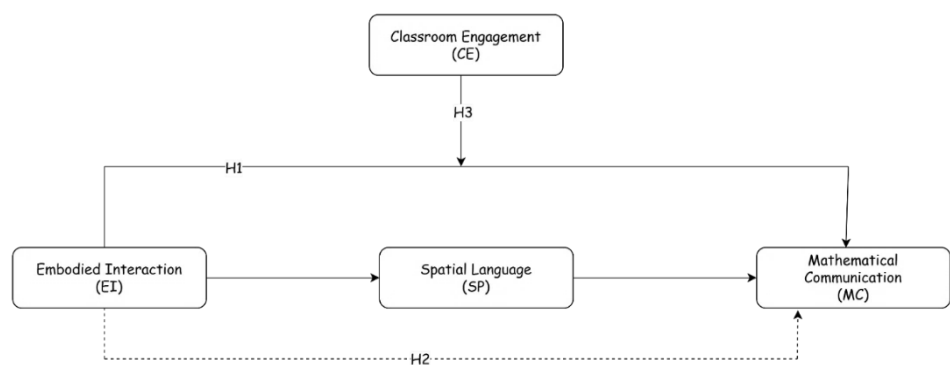


Figure 1
Hypothesized Model (Source: Author’s Constructs, 2026)

RESEARCH METHOD

Research Design

The study employed a quantitative cross-sectional design anchored in a post-positivist paradigm and utilized Structural Equation Modeling (SEM) to test the hypothesized relationships among variables. The use of SEM aligns with post-positivist assumptions by enabling researchers to assess latent constructs, account for measurement error, and examine complex causal pathways involving direct, indirect, and conditional effects (Byrne, 2016; Hair et al., 2022; Kline, 2023).

Population, Sample Size, and Sample Technique

The study population comprised 4,650 SHS 2 and SHS 3 students from three senior high schools in the Ahafo Region of Ghana. Mathematics is a compulsory subject for all students, ensuring comparable exposure to mathematics instruction. An a priori sample size calculation for Structural Equation Modeling (SEM), based on an anticipated effect size of 0.30, statistical power of 0.80, significance level of 0.05, four latent variables, and 24 observed variables, indicated a minimum sample of 137 participants. Considering model complexity, a minimum of 200 respondents was required for stable SEM estimation. However, a sample of 420 students was used to improve parameter precision, model stability, and the generalizability of the findings. A multistage sampling technique was employed. Three districts were first selected through simple random sampling, and one senior high school was subsequently selected from each district. The sample was proportionately allocated to schools, class levels (SHS 2 and SHS 3), and programmes of study based on enrolment figures. Finally, students were selected using simple random sampling, ensuring adequate representation and equal chances of selection.

Table 1
Students' Background Information

Demographics	Frequency (N)	Percentage (%)
Gender	420	100
Male	198	47.1
Female	222	52.9
School	420	100
A	175	41.67
B	142	33.81
C	103	24.52
Level of Education	420	100
Form 2	205	48.8
Form 3	215	51.2

Programme	420	100
General Arts	126	30.0
Visual Art	72	17.1
Business	43	10.2
General Science	74	17.6
Home Economics	63	15.0
Agricultural Science	42	10.0

Questionnaire and Measure

Data were collected using a structured questionnaire comprising five sections. The first section captured participants’ demographic characteristics, including gender, age, and programme of study. The remaining sections measured the study variables: Embodied Interaction (EI), Spatial Language (SL), Classroom Engagement (CE), and Mathematical Communication (MC). All items were measured on a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The items were adapted from established instruments in the literature to ensure validity and reliability. Specifically, the Embodied Interaction scale was adapted from Abrahamson (2014, 2020), Alibali et al. (2023), and Nathan (2021); the Spatial Language scale from Pruden et al. (2021), Verdine et al. (2017), Atit et al. (2022), and Purpura et al. (2017); the Classroom Engagement scale from Fredricks et al. (2004) and Bond et al. (2020); and the Mathematical Communication scale from NCTM (2014), Sfard (2021), and Bicer et al. (2020).

The instrument was pilot-tested with 37 senior high school students who were not included in the main study. Feedback from the pilot informed revisions to improve item clarity and suitability. Reliability analysis yielded Cronbach’s alpha coefficients above the recommended threshold of 0.70, indicating satisfactory internal consistency. Reliability was subsequently reassessed using the full study sample during the main analysis.

Ethical Consideration

Ethical approval was obtained from the USTED Institutional Ethics and Research Committee, and permission to conduct the study was granted by the participating schools. Informed consent was obtained from all participants, and participation was voluntary. Confidentiality and anonymity were maintained by excluding personal identifiers and securely storing all research data.

Data Analysis

The data analysis in this study aimed to assess the relationships among embodied interaction, spatial language, classroom engagement, and mathematical

communication among senior high school students in Ghana. Through Structural Equation Modeling (SEM), the research hypotheses were tested, and the direct, mediating, and moderating effects among the study variables were identified. The analysis was conducted using SPSS for preliminary analyses and AMOS for Confirmatory Factor Analysis (CFA) and Structural Equation Modeling. In addition, age, gender, and programme of study were controlled for in the analysis to account for their potential influence on mathematical communication.

Data Preparation and Cleaning

The data were coded and analysed using SPSS. Prior to analysis, the dataset was screened for missing values, data entry errors, outliers, normality, and multicollinearity. Cases with substantial missing data were removed using listwise deletion. All questionnaire items were measured on a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The screening results indicated that the data were suitable for subsequent reliability, validity, and structural equation modelling analyses.

Model-Fit Specification

The hypothesised SEM model shown in Figure 1 was estimated using AMOS 23.

$$SL = \alpha_0 + \alpha_{1EI} + \varepsilon_1$$

$$MC = \beta_0 + \beta_{1EI} + \beta_{2SL} + \varepsilon_2$$

$$MC = \gamma_0 + \gamma_{1EI} + \gamma_{2CE} + \gamma_{3(EI \times CE)} + \varepsilon_3$$

$$MC_i = \beta_0 + \beta_{1EI_i} + \beta_{2SL_i} + \beta_{3CE_i} + \beta_{4(EI \times CE)_i} + \beta_{5Age_i} + \beta_{6Gender_i} + \beta_{7Programme_i} + e_i$$

Validity and Reliability Assessment

Exploratory Factor Analysis (EFA)

An Exploratory Factor Analysis (EFA) was conducted in IBM SPSS Statistics Version 23 to assess the suitability of the measurement items and their underlying factor structure. Following the recommendation of Hair et al. (2022), items with factor loadings of 0.50 or higher were retained. The initial measurement model comprised 19 items across four constructs: Embodied Interaction (EI), Spatial Language (SL), Classroom Engagement (CE), and Mathematical Communication

(MC). All retained items loaded strongly on their respective constructs, with factor loadings ranging from 0.738 to 0.814 and no substantial cross-loadings, providing preliminary evidence of construct validity. The rotated solution yielded four factors corresponding to the hypothesised constructs. Four items were retained for Embodied Interaction, and five items each were retained for Spatial Language, Classroom Engagement, and Mathematical Communication (Table 2). The four factors explained 68.22% of the total variance, exceeding the recommended threshold of 50% (de Winter et al., 2009). The adequacy of the data for factor analysis was confirmed by a Kaiser-Meyer-Olkin (KMO) value of 0.924 and a significant Bartlett’s Test of Sphericity ($\chi^2 = 4168.279$, $df = 171$, $p < .001$), indicating that the dataset was suitable for factor analysis.

Table 2
Exploratory Factor Analysis (EFA), KMO, Bartlett's test, TVE, and Determinant

Measurement items	Component			
	1	2	3	4
<i>Rotated Component matrix</i>				
SL3	.791			
SL5	.780			
SL1	.768			
SL6	.745			
SL2	.743			
MC3		.802		
MC2		.774		
MC5		.764		
MC4		.754		
MC6		.746		
CE3			.814	
CE4			.802	
CE5			.796	
CE1			.778	
CE6			.776	
EI5				.778
EI6				.763
EI3				.762
EI2				.738
Kaiser-Meyer-Olkin Measure of Sampling Adequacy				0.924
Bartlett's Test of Sphericity			Approx. Chi-Square	4168.279
			Df	171
			sig	.0000
Determinant				3.208E-5
Total Variance Explained				68.224%

Common Method Bias

Common Method Bias (CMB) was considered in this study because data for all constructs were collected from the same respondents using self-report questionnaires, which can introduce systematic measurement error (Podsakoff et al., 2003). The primary defense against CMB in this study was procedural. Items were kept anonymous and confidential to minimize social desirability bias, responses were clearly informed that there were no right or wrong answers. The questionnaire items were also written in simple language and organized into separate sections to reduce response patterns and method-related effects (Podsakoff et al., 2003). A statistical check, Harman's single-factor test was also conducted. An unrotated principal component analysis of all items measuring Embodied Interaction, Spatial Language, Classroom Engagement, and Mathematical Communication revealed four factors with eigenvalues greater than 1. The first factor (Spatial Language) explained 38.75% of the total variance, which is below the 50% threshold suggested by Podsakoff et al. (2003). A non-dominant first factor does not by itself rule out method-related inflation of the correlations among constructs (Podsakoff et al., 2003). Two further indicators supplement this check. None of the bivariate correlations among the study's constructs exceeded 0.9, and the HTMT ratios reported in Table 4 were likewise all below the conservative 0.9 threshold. Taken together, the procedural safeguards implemented during data collection, rather than the Harman's test results alone, are treated as the primary basis for concluding that common method bias was unlikely to have seriously biased the study's findings.

Confirmatory Factor Analysis (CFA)

Following the EFA, Confirmatory Factor Analysis (CFA) was performed in AMOS Version 23 to validate the measurement model. Only items retained from the EFA were included in the analysis (Hair et al., 2022; Worthington & Whittaker, 2006). All standardized factor loadings exceeded the recommended threshold of 0.50, ranging from 0.66 to 0.84, indicating that the retained items adequately represented their respective constructs (Table 3). Reliability and convergent validity were assessed using Cronbach's Alpha (CA), Composite Reliability (CR), and Average Variance Extracted (AVE). As shown in Table 3, all constructs exceeded the recommended thresholds of 0.70 for CA and CR and 0.50 for AVE (Haji-Othman & Yusuff, 2022), confirming satisfactory reliability and convergent validity. The measurement model demonstrated a good fit to the data ($\chi^2 = 303.843$, $df = 146$, $\chi^2/df = 2.081$, $GFI = 0.924$, $TLI = 0.956$, $CFI = 0.962$, $SRMR = 0.038$, $RMSEA = 0.051$, $PCLOSE = 0.381$), with all fit indices meeting recommended criteria (Hermida, 2015; Kline, 2018; Xia & Yang, 2019). Discriminant validity was evaluated using the Heterotrait-Monotrait Ratio (HTMT). All HTMT values

(Table 4) were below the recommended threshold of 0.90 (Henseler et al., 2015), providing evidence of satisfactory discriminant validity. The CFA results confirmed that the measurement model possessed adequate reliability, convergent validity, discriminant validity, and model fit, providing a sound basis for the subsequent structural model analysis.

Table 3
Confirmatory Factor Analysis (CFA) and Model Fit Indices

Model Fit Indices: CMIN= 303.843; DF= 146; CMIN/DF= 2.081; GFI= 0.924; TLI= 0.956; CFI= 0.962; SRMR= 0.0384; RMSEA= 0.051; PCLOSE= 0.381	Std Factor Loadings
EMBODIED INTERACTION (EI): CA= 0.858; CR= 0.858; AVE = 0.601	
EI2	0.78
EI3	0.79
EI5	0.79
EI6	0.74
SPATIAL LANGUAGE (SL): CA= 0.886; CR= 0.887; AVE= 0.611	
SL1	0.77
SL2	0.77
SL3	0.84
SL5	0.83
SL6	0.69
CLASSROOM ENGAGEMENT (CE):CA=0.862; CR=0.863; AVE = 0.559	
CE1	0.66
CE3	0.80
CE4	0.76
CE5	0.78
CE6	0.73
MATHEMATICAL COMMUNICATION (MC): CA= 0.874; CR =0.875; AVE= 0.584	
MC2	0.81
MC3	0.78
MC4	0.68
MC5	0.84
MC6	0.70

Table 4
HTMT for Discriminant Validity

Constructs	EI	SL	CE	MC
EI	----	----	----	----
SL	0.698	----	----	----
CE	0.358	0.261	----	----
MC	0.626	0.617	0.389	----

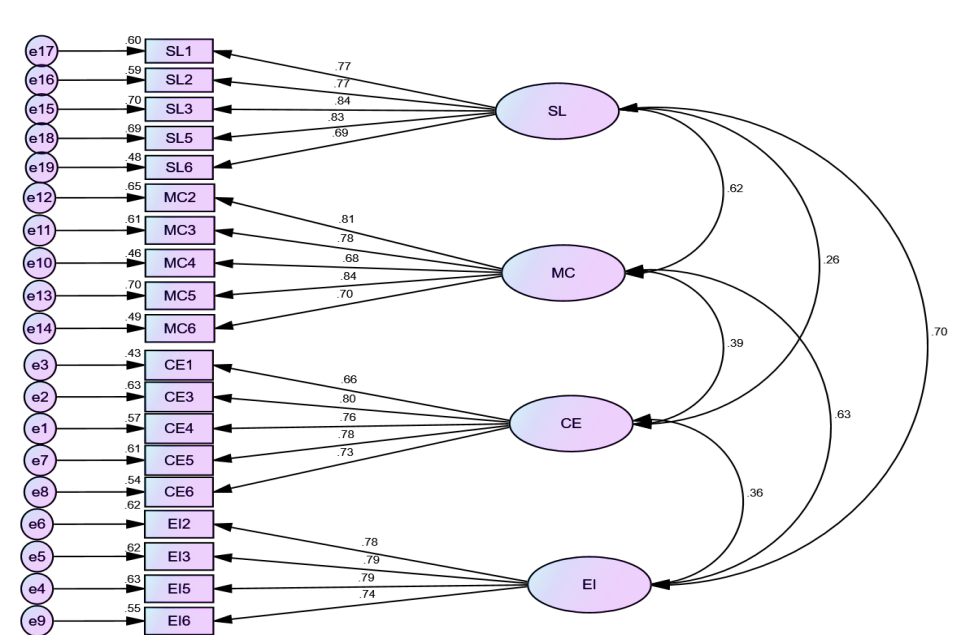


Figure 2
Confirmatory Factor Analysis (Source: Authors' Creation, 2025)

RESULTS

Path Analysis

Table 5 shows a summary of both direct and indirect effects. The results showed that embodied interaction significantly predicted mathematical communication ($\beta = 0.321$, S.E. = 0.041, C.R. = 10.938, $p < .001$), supporting H1. Embodied interaction significantly predicted spatial language ($\beta = 0.751$, S.E. = 0.061, C.R. = 12.266, $p < .001$), and spatial language significantly predicted mathematical communication ($\beta = 0.279$, S.E. = 0.057, C.R. = 4.850, $p < .001$). Together, embodied interaction and spatial language accounted for 46% proportion

of the variance in mathematical communication. Also, embodied interaction accounted for 49% (R^2) proportion of variance in spatial language. The direct effect of embodied interaction on mathematical communication remained significant after including spatial language in the model ($\beta = 0.321$, $p < .001$), indicating partial mediation. The bootstrapped indirect effect was significant (indirect effect = 0.209, 95% BC CI [0.114, 0.293]), supporting H2.

Table 5
Summary of Path Analysis

Direct effect	Std. estimate	S.E.	C.R.	P
SL <--- EI	.751	.061	12.266	***
MC <--- EI	.321	.063	5.094	***
MC <--- SL	.279	.057	4.850	***
Indirect effect	Std. estimate	Lower (BC)	Upper BC	
EI → SL → MC	0.209	0.114	0.293	<00.1

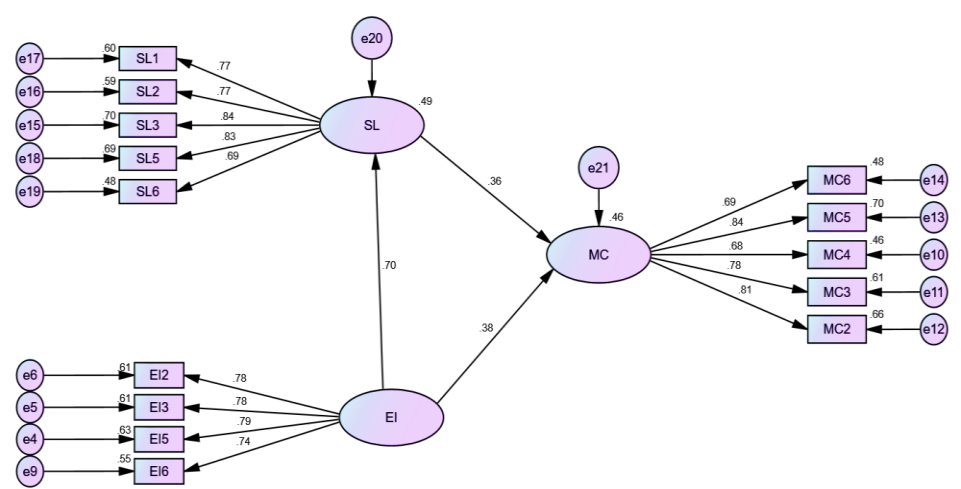


Figure 3
Path model

To examine whether classroom engagement moderated the relationship between embodied interaction and mathematical communication, an interaction term (Embodied Interaction × Classroom Engagement) was entered into the

structural model. The moderation model accounted for 32% of the variance in mathematical communication ($R^2 = .32$).

Table 6
Moderation Effect

Moderating effect	Std. Est	S.E	CR	<i>p-value</i>
MC←InterEIxCE	.055	.036	1.511	.131

As shown in Figure 4, embodied interaction had a significant positive effect on mathematical communication ($\beta = .47$, $p < .001$), indicating that students with higher levels of embodied interaction demonstrated better mathematical communication. Likewise, classroom engagement significantly predicted mathematical communication ($\beta = .19$, $p < .001$), suggesting that more engaged students reported higher levels of mathematical communication. However, the interaction between embodied interaction and classroom engagement was not statistically significant ($\beta = .06$, $SE = .036$, $CR = 1.511$, $p = .131$). Therefore, classroom engagement did not significantly moderate the relationship between embodied interaction and mathematical communication. Hypothesis 3 was therefore not supported.

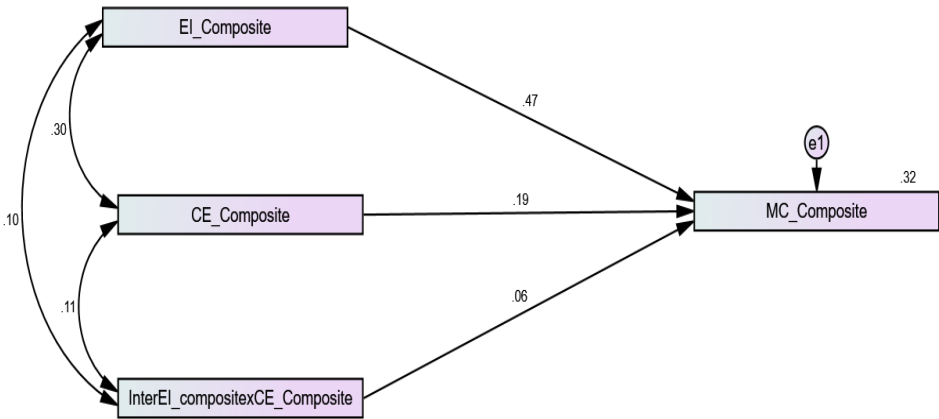


Figure 4
Moderating Path

Figure 5 presents the interaction plot for low and high levels of classroom engagement. Although students with higher classroom engagement consistently demonstrated higher mathematical communication across levels of embodied

interaction, the two regression lines are almost parallel. This indicates that the strength of the relationship between embodied interaction and mathematical communication remains relatively constant regardless of students' level of classroom engagement. Consequently, classroom engagement does not strengthen or weaken the positive effect of embodied interaction on mathematical communication.

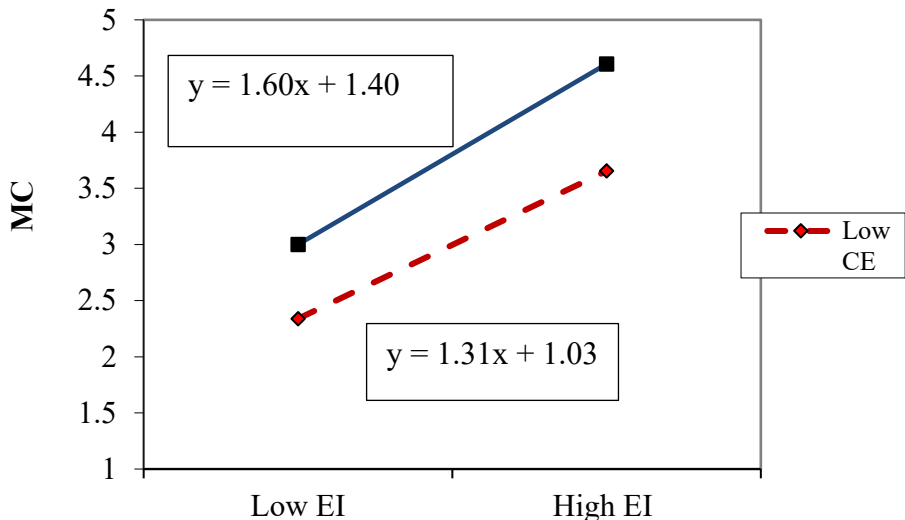


Figure 5
Two-Way Interaction Effect of Classroom Engagement (CE) on the Nexus Between Embodied Interaction and Mathematical Communication

DISCUSSION

H1: Embodied interaction has a significant positive effect on mathematical communication

The findings supported the first hypothesis, indicating that embodied interaction had a significant positive effect on mathematical communication ($\beta = 0.321, p < .001$). This suggests that students who actively engage in gestures, bodily movement, object manipulation, and other interactive learning activities are better able to explain mathematical ideas, justify solutions, interpret representations, and participate in mathematical discourse. This finding is consistent with Embodied Cognition Theory, which posits that learning is grounded in sensory and motor experiences. Through interaction with physical and symbolic representations, learners develop meaningful conceptual foundations that support the communication of mathematical ideas. The result also aligns with previous studies showing that embodied learning enhances conceptual

understanding, mathematical reasoning, and students' ability to communicate mathematical relationships (Abrahamson et al., 2020; Alibali et al., 2023; Walkington et al., 2019). A plausible explanation is that embodied interaction provides concrete experiences that can be translated into verbal and symbolic mathematical expressions. Through gestures, physical demonstrations, and object manipulation, students develop representations that make abstract ideas easier to understand and communicate. As a result, learners who engage in embodied mathematical activities may communicate their mathematical reasoning more effectively and confidently. Within the Ghanaian context, where mathematics instruction often emphasizes procedural competence and examination performance, the findings highlight the value of incorporating embodied learning strategies into classroom practice. Integrating hands-on activities, gestures, movement-based demonstrations, and manipulative materials may strengthen both students' conceptual understanding and their ability to communicate mathematical ideas.

H2: Spatial language significantly mediates the relationship between embodied interaction and mathematical communication.

The findings supported the second hypothesis, indicating that spatial language significantly mediated the relationship between embodied interaction and mathematical communication. Embodied interaction positively predicted spatial language ($\beta = 0.751, p < .001$), and spatial language, in turn, positively predicted mathematical communication ($\beta = 0.279, p < .001$). The significant bootstrapped indirect effect further confirmed the mediating role of spatial language.

This finding suggests that embodied mathematical experiences contribute to mathematical communication partly by enhancing students' spatial language. Through gestures, movement, and interaction with mathematical representations, learners develop vocabulary for describing location, direction, orientation, movement, and spatial relationships, which subsequently supports the communication of mathematical ideas. The result is consistent with Conceptual Metaphor Theory, which posits that abstract concepts are understood and communicated through bodily and spatial experiences (Lakoff & Núñez, 2000). It also aligns with previous studies showing that spatial language supports mathematical reasoning, problem-solving, and communication, while embodied experiences facilitate the development of spatial vocabulary (Atit et al., 2022; Purpura et al., 2017; Ren et al., 2022; Verdine et al., 2017).

The partial mediation observed in this study suggests that spatial language explains only part of the relationship between embodied interaction and mathematical communication. Other mechanisms, such as conceptual understanding, motivation, confidence, or cognitive engagement, may also contribute to this relationship and warrant further investigation. From a practical

perspective, the findings highlight the importance of intentionally developing students' spatial language during mathematics instruction. Encouraging learners to describe positions, movements, transformations, and spatial relationships may strengthen both their spatial language proficiency and their ability to communicate mathematical ideas, particularly in geometry, measurement, graphing, and spatial reasoning.

H3: Classroom engagement significantly moderates the relationship between embodied interaction and mathematical communication.

The findings did not support the third hypothesis. Although classroom engagement significantly predicted mathematical communication ($\beta = 0.199$, $p < .001$), its interaction with embodied interaction was not significant ($\beta = 0.055$, $p = .131$). This suggests that the positive effect of embodied interaction on mathematical communication was relatively consistent across different levels of classroom engagement.

This finding differs from expectations based on the 4E Cognition Framework, which emphasizes the role of learners' interactions with their physical and social environments in shaping learning outcomes (Newen et al., 2018). It was expected that highly engaged students would derive greater communicative benefits from embodied learning experiences. However, the absence of a significant interaction effect indicates that classroom engagement does not strengthen or weaken the influence of embodied interaction on mathematical communication. Embodied learning activities inherently promote active participation through gestures, movement, and object manipulation (Abrahamson et al., 2020; Alibali et al., 2023). As a result, embodied interaction may provide similar communicative benefits to students regardless of their reported engagement levels.

The findings suggest that classroom engagement and embodied interaction may operate through distinct pathways. While engagement contributes through students' attention, effort, and participation, embodied interaction contributes through sensory, motor, and experiential learning processes. This interpretation is consistent with the view that engagement functions primarily as a direct predictor of learning outcomes rather than a condition that modifies instructional effects (Kahu & Nelson, 2018).

Despite the non-significant moderation effect, classroom engagement remained a significant predictor of mathematical communication. The findings therefore suggest that engagement and embodied interaction independently contribute to students' ability to communicate mathematical ideas. For mathematics teachers, this implies that embodied instructional strategies such as gesture use, hands-on activities, physical modelling, and movement-based learning can be implemented effectively across students with varying levels of classroom engagement.

CONCLUSIONS

This study examined how embodied interaction influences mathematical communication among senior high school students in Ghana, with spatial language serving as a mediator and classroom engagement as a moderator. The results indicate that students who engage in gestures, movement, object manipulation, and other embodied learning activities are better able to communicate mathematical ideas. In addition, spatial language was found to partially mediate this relationship, suggesting that embodied learning enhances mathematical communication not only through direct experience but also by strengthening students' use of spatial vocabulary and expressions.

Although classroom engagement was expected to strengthen the relationship between embodied interaction and mathematical communication, no significant moderating effect was found. However, classroom engagement independently predicted mathematical communication, indicating that while engaged students generally communicate mathematical ideas more effectively, the positive influence of embodied interaction is evident regardless of students' level of classroom engagement.

This study adds to the growing body of research on embodied mathematics learning by demonstrating the complementary roles of embodied interaction and spatial language in supporting mathematical communication. The findings provide further evidence for Embodied Cognition Theory and Conceptual Metaphor Theory while offering practical implications for mathematics education. Mathematics teachers should integrate embodied learning activities into classroom instruction and deliberately encourage the use of spatial language to help students explain, justify, and communicate mathematical ideas more effectively in Ghanaian classrooms.

AI DISCLOSURE STATEMENT

The authors used ChatGPT by OpenAI to assist with language polishing, including improvements in grammar, sentence flow, clarity, and readability. The tool was not used for data generation, statistical analysis, interpretation of results, or development of scientific conclusions. All content was critically reviewed and approved by the authors, who take full responsibility for the final manuscript.

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Bios

EMMANUEL KUSI is an MPhil student in Mathematics Education and a Teaching Assistant at the University of Skills Training and Entrepreneurial Development (USTED), Kumasi, Ghana. His research interests include embodied cognition, spatial reasoning, mathematical communication, and educational technology in mathematics education. Email: kusie818@gmail.com

PROF. YARHANDS ARTHUR DISSOUR is a Professor of Mathematics Education at the University of Skills Training and Entrepreneurial Development (USTED), Ghana. His research interests include mathematics education, mathematics teaching and learning, and students' mathematical thinking and problem-solving.

PROF. FRANCIS OHENE BOATENG is a Professor of Mathematics Education at the University of Skills Training and Entrepreneurial Development (USTED), Ghana. His research interests include mathematics education, mathematics teaching and learning, and research in mathematics education.

STEPHEN DANIELS SARFO is an MPhil student in Mathematics Education and a Teaching Assistant at the University of Skills Training and Entrepreneurial Development (USTED), Kumasi, Ghana. His research interests include mathematics education, mathematics teaching and learning, educational technology, and curriculum studies. Email: ssarfo303@gmail.com

INNOCENT AKPAGE is an MPhil student in Mathematics Education and a Teaching Assistant at the University of Skills Training and Entrepreneurial Development (USTED), Kumasi, Ghana. His research interests include mathematics pedagogy, technology-enhanced learning, mathematics curriculum development, and mathematics education. Email: innocentakpage13@gmail.com