

Participation Before Proficiency: A Three-Year Longitudinal Mixed-Methods Study of Motivation and Engagement in Bilingual STEAM Learning Through a Triple-On Learning Ecology

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Abstract

Background

The convergence of competency-based STEAM reforms and Taiwan's Bilingual 2030 Policy has stimulated growing interest in Content and Language Integrated Learning (CLIL) as an approach to bilingual STEAM education. Within such contexts, sustaining learners' motivation and engagement remains a central challenge, particularly when students are expected to participate in cognitively demanding disciplinary practices through an emerging second language. Young learners frequently encounter a cognitive–linguistic bottleneck when engaging in inquiry, engineering design, and problem-solving through an emerging second language. Although previous studies have documented the benefits of CLIL, little is known about how learners' motivation and engagement are sustained, how bilingual STEAM participation develops longitudinally, or how pedagogical mediation supports learners when linguistic resources lag behind disciplinary demands. This three-year mixed-methods case study examined a vertically articulated CLIL-STEAM curriculum to investigate students' English achievement, learning experiences, and the ecological processes that shaped bilingual participation across Grades 4 to 6 in a Taiwanese public primary school (N = 89).

Results

Semester-level analyses indicated significantly higher English achievement during CLIL-STEAM intervention semesters than during adjacent non-intervention semesters in Grades 4 and 5, with moderate effect sizes, whereas the Grade 6 comparison was not statistically significant. Across the three-year period, intervention-semester composites exceeded non-intervention composites by 2.68 points, $t(88) = 6.35$, $p < .001$, Cohen's $d_z = 0.67$, a pattern further supported by linear mixed-effects modeling. Qualitative analyses of annual focus group interviews, classroom observations, and student artifacts revealed that bilingual participation and learner engagement were sustained despite persistent language anxiety. Three interrelated patterns emerged: (1) hands-on design and peer collaboration provided equitable entry points for participation regardless of English proficiency; (2) purposeful communication and multimodal resources enabled students to negotiate linguistic challenges while engaging in disciplinary inquiry; and (3) repeated engagement with civic-oriented STEAM projects repositioned English from a test-oriented subject to a functional resource for problem-solving and public communication, thereby strengthening learners' motivation for meaningful language use. These developmental processes were mediated through material prototyping, multimodal representation, and trans-semiotizing practices that expanded students' opportunities for meaningful participation and communication.

Conclusion

The findings suggest that bilingual STEAM development is better understood as a mediated, non-linear process than as language acceleration alone. The proposed *Triple-On Learning Ecology* explains this process through the interaction of Head-On disciplinary challenge, Hands-On material and multimodal mediation, and Minds-On collaborative meaning-making. The study argues that participation can precede proficiency, competence can be distributed across learners and semiotic resources, and communicative agency can emerge through authentic disciplinary practice. By demonstrating how authentic participation sustains learners' motivation and engagement while language proficiency is still developing, the study contributes to current discussions on learner engagement, CLIL, and second language learning in interdisciplinary educational contexts.

1. Introduction

1.1 Global STEAM Trends and Taiwan's Bilingual Turn

Over the past two decades, integrated STEM and STEAM education has emerged as a global reform movement, expanding disciplinary integration to include the arts and design thinking (Bybee, 2013; English, 2016; Herro et al., 2017; Honey et al., 2014; National Research Council, 2012; Ortiz-Revilla et al., 2023; Perignat & Katz-Buonincontro, 2019; Quigley & Herro, 2016; Yakman, 2008). These global movements have substantially catalyzed macroeconomic and educational policy reforms worldwide, including in Taiwan.

The implementation of the 12-Year Basic Education Curriculum Guidelines (commonly referred to as the 108 Competency-Based Curriculum) marked a significant transition from passive knowledge transmission toward competency-based education, emphasizing interdisciplinary learning, inquiry, communication, and civic participation (Ministry of Education [MOE], 2018). Building upon this reform, Taiwan's Bilingual 2030 Policy has further encouraged schools to integrate English across content subjects through bilingual and English-medium instructional approaches, with the broader goal of cultivating globally competent citizens capable of participating in international academic, professional, and intercultural communities (Ministry of Education [MOE], 2021; National Development Council [NDC], 2018; Gupta & Lin, 2023; Huang, 2024; Yeh, 2023).

Despite these ambitious policy goals, research has documented a persistent gap between policy aspirations and classroom implementation, highlighting the challenges teachers face in translating top-down bilingual mandates into effective instructional practices (Chen et al., 2020). Consequently, language learning is increasingly expected to occur not only as a school subject but also through meaningful engagement with disciplinary knowledge. This implementation gap has also been documented in Taiwanese primary STEAM classrooms (Lin & Wu, 2021; Wang, 2024). Empirical accounts from Taiwan indicate persistent incongruity between top-down bilingual mandates and what teachers can enact in classrooms (Chen et al., 2020; Graham & Yeh, 2023), and public orientations toward the policy itself remain contested (Chang, 2025).

Within this policy landscape, Content and Language Integrated Learning (CLIL) has emerged as one of the most influential pedagogical approaches for bilingual education. Rather than conceptualizing English as a discrete subject, CLIL positions language as a functional resource that supports disciplinary

inquiry, communication, and knowledge construction (Coyle et al., 2010; Dalton-Puffer, 2011; Nikula et al., 2016). Recent studies have reported that CLIL can promote both disciplinary understanding and communicative competence, particularly when language is embedded within authentic problem-solving contexts (Dalton-Puffer & Smit, 2020a; Llinares et al., 2012; Mettewie et al., 2024; Pérez-Cañado, 2020). At the same time, STEAM education offers naturally meaningful contexts in which language becomes a tool for explaining evidence, negotiating ideas, documenting designs, and communicating solutions (English & King, 2019; Kelley & Knowles, 2016). Within Taiwan, CLIL has been progressively localized rather than transplanted, moving from the borrowed 4Cs framework toward globalized, ELF-informed configurations (Huang & Tsou, 2023).

However, the convergence of CLIL and STEAM also challenges assumptions that greater English exposure will automatically produce corresponding gains in language proficiency. In primary classrooms, learners must often coordinate emerging English resources with unfamiliar disciplinary concepts, collaborative interaction, technological tools, and engineering design. Understanding bilingual STEAM learning therefore requires attention not only to instructional input and measurable outcomes, but also to the motivational, social, and ecological processes through which learners gain access to participation, sustain engagement, and construct meaning over time.

1.2 The Cognitive–Linguistic Challenge of Bilingual STEAM Learning

CLIL-STEAM creates a distinctive learning environment because students are expected to engage in disciplinary reasoning while simultaneously communicating through a developing second language. Unlike conventional language classrooms, bilingual STEAM learning requires students to investigate scientific phenomena, interpret multimodal representations, construct and evaluate engineering prototypes, negotiate collaborative problem solving, and explain evidence-based design decisions through discipline-specific cognitive discourse functions such as describing, explaining, interpreting, evaluating, and justifying (Morton, 2020). These disciplinary practices closely align with contemporary science education frameworks that emphasize scientific inquiry, engineering design, evidence-based reasoning, and the intentional integration of disciplinary knowledge as core components of K–12 STEM learning (National Research Council, 2012; Ortiz-Revilla et al., 2023). Such interdisciplinary integration is widely recognized as a defining characteristic of STEAM education, where scientific inquiry, engineering design, creativity, and collaborative problem solving are intentionally connected to support authentic learning experiences (Yakman, 2008; Perignat & Katz-Buonincontro, 2019). Consequently, these concurrent disciplinary and linguistic demands place substantial cognitive and linguistic pressure on learners, particularly when the complexity of disciplinary inquiry exceeds their available linguistic resources or working memory capacity (Dalton-Puffer & Smit, 2020a, 2020b; Llinares et al., 2012; Sweller, 2011, 2020). From a CLIL perspective, successful participation therefore depends not only on acquiring content knowledge but also on the ability to coordinate disciplinary thinking and language use simultaneously (Coyle et al., 2010). School-level evidence from Taiwan similarly identifies wide within-class proficiency gaps and learners' reluctance to speak English as a central pedagogical challenge in bilingual subject teaching (Wang, 2024).

The challenges of bilingual STEAM learning are not exclusively cognitive but also affective. Students are often expected to communicate disciplinary ideas orally while learning through English, which may generate anxiety related to pronunciation, grammatical accuracy, public performance, and fear of negative evaluation (Horwitz et al., 1986; MacIntyre & Gardner, 1994). Such challenges are particularly salient in bilingual and CLIL classrooms, where English is frequently associated with testing, correctness, and academic achievement, reducing learners' willingness to take communicative risks (Dewaele & MacIntyre, 2014; Graham et al., 2017). Consequently, students may remain silent, defer to more proficient classmates, or contribute primarily through hands-on activities while limiting verbal participation (MacIntyre et al., 1998; Nikula et al., 2016). Differences in English proficiency may therefore translate into unequal opportunities for disciplinary participation, collaborative knowledge construction, and identity development.

Yet participation in bilingual STEAM is mediated through far more than spoken language alone. Learners construct meaning by coordinating multiple semiotic resources, including diagrams, gestures, mathematical symbols, physical models, digital technologies, first-language resources, peer interaction, and artistic representations that are increasingly recognized as integral components of STEAM learning (Cope & Kalantzis, 2015; Jewitt, 2014; Kress, 2010; Land, 2013; Quigley & Herro, 2016; Zhang & Jia, 2024). These multimodal resources make disciplinary concepts more accessible, distribute cognitive demands across learners, artifacts, and technological tools (Hutchins, 1995), and broaden the range of legitimate ways students can demonstrate understanding and contribute to collaborative inquiry (Mercer & Littleton, 2007; van Leeuwen, 2005; Zheng et al., 2025). Rather than merely compensating for limited English proficiency, multimodality can reshape what counts as competent participation in bilingual STEAM classrooms by recognizing learners' diverse linguistic and semiotic resources as legitimate means of disciplinary meaning-making, consistent with perspectives on equitable multilingualism (Ortega, 2020). Adopting an expansive view of language—one that treats gesture, drawing, modelling, and mathematical representation as legitimate semiotic resources—reframes what counts as multilingual students' scientific sensemaking (González-Howard et al., 2023). Close analysis of emergent bilingual children problematizing physical phenomena shows how learners recruit their full repertoires to enter disciplinary inquiry well before their English is adequate to it (Suárez, 2020), and a systematic review of K–12 science settings documents comparable patterns across diverse socio-geographic contexts while calling explicitly for closer integration between STEM and bilingual education research (Hou et al., 2025). Reviewed through an equity lens, multilingual meaning-making in science and engineering education functions less as a compensatory strategy than as a means of dismantling linguistic gatekeeping in disciplinary participation (Grapin et al., 2025).

This creates an important analytical problem. Language achievement and meaningful participation may not develop at the same rate or become visible through the same forms of assessment. From the perspective of equitable multilingualism, learners' disciplinary engagement should not be evaluated solely through conventional measures of English proficiency but also through their ability to participate meaningfully using diverse linguistic and semiotic resources (Lo & Fung, 2020; Ortega, 2020). Students may demonstrate only modest gains in English proficiency while becoming increasingly capable of scientific reasoning, collaboration, multimodal communication, and disciplinary engagement (Lantolf et al., 2015; Mercer, 2019; Nikula et al., 2016). A more process-oriented perspective is therefore needed to explain how learners' motivation, engagement, and participation are sustained when linguistic development remains uneven and A more process-oriented perspective is therefore needed to explain how motivation, participation, and disciplinary learning can be sustained even when linguistic development remains uneven and the demands of bilingual STEAM learning continue to increase.

1.3 Research Gap and Contributions of the Present Study

Despite growing interest in CLIL-STEAM, three gaps remain in the literature. First, most studies have examined short-term interventions or cross-sectional outcomes, providing limited evidence of how bilingual STEAM learning develops across multiple years of primary education. Second, research has frequently prioritized language scores and content achievement while giving less attention to the mediating processes through which learners sustain motivation, engagement, participation, collaboration, manage anxiety, and construct meaning through multiple semiotic resources. Third, young learners' perspectives remain insufficiently represented, particularly regarding how motivation, engagement, English use, disciplinary challenge, peer support, and communicative purpose interact during sustained bilingual learning.

The present study addresses these gaps by following one primary-school cohort across a vertically articulated, three-year project-based CLIL-STEAM curriculum. Quantitative evidence of English achievement is integrated with qualitative data from focus group interviews, classroom observations, and student learning artifacts. This design enables the study to examine both observable achievement patterns and the classroom processes through which bilingual participation was supported or constrained.

The study makes three contributions. First, it provides longitudinal evidence from Grades 4 to 6, a period rarely examined in sustained CLIL-STEAM research. Second, it shifts attention from achievement outcomes alone to the motivational and participatory processes through which disciplinary challenge, multimodal mediation, collaboration, and communicative purpose sustain learners' engagement over time. Third, it advances the *Triple-On Learning Ecology* as a provisional, process-oriented framework for explaining how bilingual STEAM participation may be sustained through the interaction of Head-On cognitive-linguistic engagement, Hands-On material mediation, and Minds-On collaborative meaning-making and agency.

1.4 Research Purpose and Questions

This three-year longitudinal mixed-methods case study investigates how primary learners' English achievement and bilingual STEAM participation developed within a sustained project-based CLIL-STEAM curriculum. It further examines how learners' motivation, engagement, and learning experiences evolved and how the curriculum's multimodal, collaborative, and transdisciplinary features mediated their responses to linguistic and disciplinary challenges.

RQ1: What is the longitudinal effect of a three-year CLIL-STEAM curriculum on primary school students' English language proficiency?

RQ2: How do learners' motivation, engagement, participation, and experiences develop across the three-year CLIL-STEAM curriculum?

RQ3: How do the project-based, multimodal, and transdisciplinary features of the curriculum mediate students' language use, learning processes, and their responses to linguistic and cognitive challenges?

2. Theoretical Framework

The present study is situated at the intersection of Content and Language Integrated Learning (CLIL), STEAM education, multimodality, and sociocultural perspectives on learning. Rather than treating language learning as the acquisition of discrete linguistic forms, these complementary perspectives conceptualize language learning as a process of participation in meaningful disciplinary practices. Together, they suggest that learners' motivation, engagement, and communicative development are not solely individual psychological attributes but are socially, materially, and pedagogically mediated through authentic classroom activity. This orientation is especially relevant to young learners, whose disciplinary reasoning may exceed what they can yet express in English. An exclusive focus on proficiency can obscure the material, interactional, and motivational processes through which they gain access to bilingual activity. This section therefore considers CLIL-STEAM as a language-mediated context, multimodality as a semiotic resource, and social participation as a basis for agency. It then integrates these perspectives into the proposed *Triple-On Learning Ecology*, a process-oriented framework explaining how bilingual participation may develop longitudinally.

2.1 CLIL-STEAM as a Language-Mediated Context for Disciplinary Inquiry

CLIL integrates language and content learning by positioning language as a functional resource for disciplinary inquiry, meaning negotiation, knowledge construction, and communication (Coyle et al., 2010; Dalton-Puffer, 2011; Dalton-Puffer & Smit, 2020a; Nikula et al., 2016). In STEM and STEAM education, learners use language to formulate hypotheses, explain evidence, justify design decisions, negotiate solutions, and communicate findings. Language learning is thus embedded within purposeful disciplinary activity rather than separated from it (English & King, 2019; Kelley & Knowles, 2016). Systematic review of the past decade indicates that research on multilingual resources in EMI and CLIL classrooms has expanded rapidly yet remains dominated by short-term, secondary-level studies (Lu et al., 2025), while longitudinal case work in science settings suggests that motivational benefits emerge when CLIL principles are deliberately layered onto content instruction rather than assumed from English exposure alone (Nieto Moreno de Diezmas et al., 2024).

Research indicates that CLIL can support disciplinary understanding and language development when tasks foster authentic communication and meaningful interaction (Dalton-Puffer & Smit, 2020a, 2020b; Llinares et al., 2012; Mettwie et al., 2024; Morton, 2020; Pérez-Cañado, 2020). Such outcomes, however, do not result from increased English exposure alone. They depend on environments that enable learners to participate actively and tolerate linguistic uncertainty. When English functions as a tool for achieving disciplinary goals rather than primarily as an object of evaluation, learners may be more willing to communicate and sustain engagement.

The convergence of CLIL and STEAM nevertheless creates a cognitive-linguistic challenge. Primary learners must use an emerging second language while reasoning about unfamiliar concepts, collaborating, and solving complex problems. Their linguistic resources may develop more slowly than the cognitive demands of inquiry and engineering design. Successful participation therefore cannot be explained by proficiency alone. It also depends on the ecological

conditions that keep learners engaged and communicatively active while their English is still developing. This raises a central question: *How can meaningful participation be sustained when learners' linguistic resources remain limited?*

2.2 Multimodality as a Semiotic Resource for Meaning-Making

One response to this question comes from multimodal theories of communication. Multimodality proposes that meaning is constructed through coordinated semiotic resources, including language, images, gestures, diagrams, physical objects, digital technologies, mathematical representations, and spatial arrangements (Cope & Kalantzis, 2015; Kress, 2010). In bilingual STEAM classrooms, these resources are integral to disciplinary reasoning. Learners may communicate ideas through sketches, prototypes, simulations, gestures, and demonstrations before expressing them fluently in English. These resources also provide alternative pathways for participation, reducing the communicative risks associated with limited proficiency. A learner who hesitates to speak may still manipulate materials, interpret a diagram, construct a model, or coordinate a group task. Successful contributions can strengthen confidence, sustain engagement, and encourage further English use. Participation consequently extends beyond spoken language to encompass multiple legitimate forms of disciplinary contribution.

This view aligns with trans-semiotizing, through which learners move flexibly across linguistic and non-linguistic resources to construct disciplinary meaning (Hou et al., 2025; Jakobsson et al., 2021; Lin, 2019; Lin, 2022; Pérez-Cañado, 2020; Suárez, 2020). First-language use, gesture, visual representation, and material artefacts are therefore not necessarily obstacles to English learning; they can serve as complementary resources for conceptual understanding and bilingual communication. Bilingual competence is better understood as an emergent capacity to coordinate “linguaging” with multiple semiotic resources to participate meaningfully in disciplinary activity than as individual linguistic proficiency alone.

2.3 Social Participation as a Developmental Mechanism for Learner Agency

While CLIL emphasizes meaningful language use and multimodality expands available communicative resources, sociocultural perspectives further suggest that learning develops through participation in socially organized activity and interaction with peers, teachers, cultural tools, and the learning environment (Lave & Wenger, 1991; Vygotsky, 1978). Language learning is consequently inseparable from opportunities to ask questions, negotiate ideas, explain reasoning, provide feedback, and solve problems collaboratively. Through such practices, communicative competence, disciplinary understanding, and learner agency can develop together.

An ecological perspective extends this view by suggesting that motivation should not be understood solely as an internal psychological characteristic that precedes participation. Rather, motivation can itself emerge through successful participation in socially meaningful activity. As learners contribute ideas, experience collaborative success, solve authentic problems, and receive recognition from peers and teachers, continued participation reinforces both learner agency and sustained engagement. In this sense, participation is not merely the outcome of motivation; it also becomes a source of motivation (Dörnyei, 2019; MacIntyre et al., 1998; Mercer, 2019; Mystkowska-Wiertelak & Pawlak, 2017).

This reciprocal relationship is particularly relevant in bilingual STEAM classrooms, where learners frequently encounter linguistic uncertainty. Rather than waiting until they achieve high levels of English proficiency before participating, learners often begin by contributing through gestures, prototypes, visual representations, first-language resources, or partial English expressions. Positive experiences can gradually expand their confidence, agency, and willingness to use English in more sophisticated ways. Agency should therefore be viewed as socially distributed and dynamically evolving, supported by collaborative interaction and access to resources that make meaningful participation possible despite uneven linguistic development.

Accordingly, learner agency should be viewed as a socially distributed and dynamically evolving process rather than as an individual disposition. Agency emerges through collaborative interaction, shared problem-solving, and access to multiple communicative resources that enable learners to participate meaningfully despite uneven linguistic development. This perspective helps explain how motivation and engagement may be sustained over extended periods even when language proficiency develops gradually.

2.4 Toward a Process Perspective on Bilingual STEAM Learning

The preceding sections collectively suggest that bilingual STEAM learning extends beyond language acquisition alone. CLIL highlights language as a disciplinary tool; multimodality foregrounds diverse resources for meaning-making; and sociocultural theory explains learning through participation, collaboration, and mediated action (Dalton-Puffer & Smit, 2020; Jewitt, 2014; Kress, 2010; Nikula et al., 2016; Vygotsky, 1978). Collectively, these perspectives suggest that motivation and engagement are intertwined with opportunities for authentic participation. Yet they are often examined separately: CLIL research commonly prioritizes language and content outcomes, multimodal studies focus on representational practices, and sociocultural studies emphasize interaction. Their compatibility has not consistently produced an integrated account of how bilingual STEAM learning unfolds longitudinally (Domke & Cerrato, 2025; Mettewie et al., 2024; Ortega, 2020). A recent systematic review across program types concludes that longitudinal accounts of how content–language integration unfolds over multiple years remain scarce (Domke & Cerrato, 2025), and an 18-month longitudinal test of CLIL found only limited within-subject effects on classroom emotions and motivation once prior language knowledge was controlled (Mettewie et al., 2024). Retrospective learner accounts point in a similar direction, suggesting that pupils enter CLIL with language-oriented expectations but come to value content-mediated communicative experience (Planckaert et al., 2026).

A common limitation across the literature is the tendency to examine these mechanisms independently. CLIL studies often focus on language and content outcomes, multimodal research examines representational practices, and sociocultural studies emphasize participation or collaboration. Although these perspectives are theoretically compatible, they are rarely integrated into a coherent explanation of how bilingual STEAM learning unfolds longitudinally within authentic classroom contexts (Domke & Cerrato, 2025; Llinares et al., 2012; Mettewie et al., 2024; Morton, 2020; Nikula et al., 2016; Ortega, 2020). Consequently, bilingual learning is frequently conceptualized as a collection of instructional components rather than as an evolving developmental process, with comparatively less attention given to how learners sustain motivation and engagement throughout this process. This limitation is particularly

consequential in policy-driven bilingual initiatives, where evaluation frequently privileges instructional hours, standardized proficiency, or content achievement (Bruton, 2020; Ministry of Education, 2021). Although important, these indicators overlook how learners sustain participation while coordinating disciplinary understanding, multimodal communication, emerging English use, and ongoing engagement with challenging learning tasks. Slow or uneven linguistic growth may then be interpreted as limited effectiveness rather than as part of a non-linear process of cognitive consolidation and expanding communicative capacity.

These observations point to the need for a process-oriented perspective that conceptualizes bilingual STEAM learning as an evolving learning ecology rather than a linear relationship between instructional input and language outcomes. From this perspective, motivation and engagement are understood not as fixed learner characteristics but as developmental processes emerging through meaningful participation, collaborative interaction, and authentic disciplinary communication. Responding to this theoretical gap, the present study proposes the *Triple-On Learning Ecology* as a process theory that explains how language-mediated disciplinary learning, multimodal meaning-making, and social participation interact to sustain motivation, engagement, and bilingual STEAM learning across extended developmental trajectories.

2.5 The *Triple-On Learning Ecology*: A Process Theory of Bilingual STEAM Learning

Building upon the preceding theoretical perspectives, this study proposes the *Triple-On Learning Ecology* as a process-oriented framework to explain how bilingual STEAM learning develops over time. It is an analytical framework rather than an instructional sequence or curriculum model. Its purpose is to elaborate how participation is initiated, sustained, and transformed under simultaneous cognitive and linguistic challenge. The term “ecology” emphasizes that learning outcomes arise from relations among learners, tasks, tools, languages, peers, and disciplinary purposes rather than from any single instructional feature. Rather than conceptualizing language mediation, multimodal meaning-making, and social participation as independent pedagogical elements, the framework argues that bilingual learning emerges through the continuous interaction of these mechanisms as learners engage in authentic disciplinary practices. As illustrated in Fig. 1, the framework consists of three interdependent dimensions—*Hands-On*, *Minds-On*, and *Head-On*—that collectively mediate learners’ developmental trajectories. These dimensions are not hierarchical or sequential; rather, they operate recursively throughout classroom activity, with each reinforcing and reshaping the others over time. Together, they provide complementary forms of mediation that enable learners to participate meaningfully despite developing English proficiency while simultaneously sustaining their motivation and engagement in disciplinary learning.

The framework is offered as a pedagogical heuristic rather than as a competing model of bilingual programme design. Localized models developed for the Taiwanese context, most notably the FERTILE model, have foregrounded flexibility, whole-school environment, sufficient time, and differentiated instruction as conditions for sustainable bilingual teaching (Lin, 2021; Lin & Wu, 2021). The Triple-On heuristic is complementary to that work but shifts the analytic focus from teacher-side implementation conditions toward learners’ mediated participation, asking how disciplinary challenge, material mediation, and collaborative meaning-making jointly sustain engagement while proficiency is still developing.

Note

The Triple-On Learning Ecology illustrates how material, epistemic, and cognitive-linguistic mediation interact dynamically within supportive environments to foster learner agency and sustain bilingual STEM learning over time. Image generated by ChatGPT (OpenAI).

Hands-On refers to material mediation, whereby physical artifacts, engineering prototypes, digital technologies, and visual representations externalize disciplinary thinking and reduce dependence on verbal language alone. Material engagement allows learners to manipulate, test, and refine ideas through tangible action, thereby creating accessible entry points into complex disciplinary practices. These artefacts function as epistemic resources for reasoning, communication, and collaborative inquiry. They can also lower communicative barriers, enabling successful participation that supports confidence and willingness to communicate in English.

Minds-On represents epistemic mediation, emphasizing learners’ active construction of disciplinary understanding through authentic problem-solving. Within this dimension, learners are positioned not as recipients of linguistic input but as emerging knowledge builders who generate explanations, evaluate evidence, and design solutions to meaningful societal problems. English becomes one resource among several for constructing and communicating disciplinary knowledge. Through meaningful contribution and collaborative success, learners therefore develop epistemic agency, while motivation and engagement are reinforced by authentic communicative purposes rather than external performance demands.

Head-On captures productive engagement with cognitive–linguistic challenge, framing challenge as an essential condition for developmental learning rather than something to be minimized. Within this dimension, learners strategically coordinate multiple semiotic resources, including their first language, emerging English, gestures, diagrams, material artifacts, and peer interaction, to negotiate increasingly sophisticated disciplinary ideas. Learning therefore becomes a process of developing resilience and communicative capacity, in which productive struggle functions as a catalyst for disciplinary understanding, language growth, learner confidence, and sustained engagement with increasingly demanding disciplinary practices.

The explanatory value of the *Triple-On Learning Ecology* lies not in the three dimensions individually, but in their dynamic interaction. Material engagement creates opportunities for participation; participation supports the development of epistemic agency; and growing agency enables learners to persist through cognitive and linguistic challenges. These successful experiences of participation further strengthen learners’ motivation and engagement, encouraging continued involvement in authentic bilingual disciplinary practices. The reciprocal relationships among participation, motivation, engagement, and communicative development allow bilingual learning to unfold as a dynamic, non-linear trajectory rather than as a simple accumulation of language knowledge (de Bot et al., 2007; Dörnyei, 2009).

The framework therefore advances three related propositions: participation may precede proficiency; competence may be distributed across learners and semiotic resources; and communicative agency may emerge through authentic disciplinary practice. These propositions shift the analytical question from

whether learners possess sufficient English to participate to how classroom ecologies enable participation while proficiency develops. By foregrounding mediation, participation, agency, motivation, and engagement, the *Triple-On Learning Ecology* provides the conceptual lens for interpreting the present findings and contributes a longitudinal, process-oriented account to bilingual STEAM education and second-language motivation research.

3. Methods

3.1 Research Design: A Longitudinal Mixed-Methods Case Study

This study adopted a three-year longitudinal, mixed-methods case study design (September 2022–June 2025) to investigate how bilingual STEAM learning develops within a sustained project-based CLIL-STEAM curriculum. Rather than conceptualizing bilingual learning as a short-term instructional outcome, the study adopted a developmental perspective that examined how learners' language use, participation, motivation, engagement, and disciplinary learning evolved through repeated engagement with increasingly complex engineering design challenges.

Methodologically, the study adopted a convergent mixed-methods design in which quantitative and qualitative evidence was collected throughout the intervention and interpreted in an integrated manner (Creswell & Plano Clark, 2018). Quantitative analyses examined longitudinal patterns in students' English achievement (RQ1), whereas qualitative evidence documented learners' motivation, engagement, collaboration, multimodal meaning-making, communicative participation, and perceptions of English use (RQ2–RQ3). Rather than treating these two strands independently, the study integrated them to explain not only whether learning outcomes changed, but also how learners sustained motivation and engagement through classroom participation within the proposed *Triple-On Learning Ecology*. Professional development needs identified in Taiwanese bilingual classrooms point to the value of school-embedded, collaborative curriculum design of this kind (Luo, 2021), and design research framed around equity-as-transformation similarly repositions multilingual learners' resources as assets to be built upon in designing science learning environments (Pierson et al., 2024).

3.2 Methodological Innovation: The Curriculum-as-Research (CaR) Approach

The study was situated within a Curriculum-as-Research (CaR) approach, in which curriculum design, classroom enactment, and empirical analysis were treated as an integrated and iterative research process rather than as separable stages. Within this framework, the curriculum itself constituted both the site and the instrument of investigation, allowing learning processes, mediating mechanisms, and developmental trajectories to be examined in situ over time. This approach was particularly suitable for investigating how learners' motivation, engagement, participation, and bilingual communication developed through sustained involvement in authentic disciplinary practices.

Table 1 provides an overview of the vertically articulated three-year CLIL-STEAM curriculum, "*We See & Think; We Build & Learn; We Care & Dare*," implemented across Grades 4–6. The curriculum was organized around authentic, civic-oriented engineering challenges that progressively increased in disciplinary complexity, communicative demands, and learner autonomy while systematically integrating the principles of the Triple-On Learning Ecology through Head-On disciplinary inquiry, Hands-On engineering design, and Minds-On collaborative meaning-making.

Grade 4 Module (Foundational): Traffic Lights the Way: No More Traffic Jams. This introductory module addressed localized pedestrian safety and vehicle miscommunication at the school community. Students engineered and programmed automated traffic signaling systems. The module integrated electrical circuits and the properties of light (Science), geometric measurement and interval calculation (Mathematics), visual communication through color and signal design (Arts), block-based programming and algorithmic thinking (Technology), and prototype construction using cardboard engineering (Engineering). Through Head-On exploration of scientific concepts, Hands-On prototyping and programming, and Minds-On collaborative discussion, students developed foundational engineering design, computational thinking, and bilingual communication skills.

Grade 5 Module (Developmental): Noise Alerts the Mind: Designing Quiet Spaces. This intermediate module focused on the environmental optimization of shared public spaces. Building on the previous year's engineering experiences, students investigated noise pollution in shared public spaces, such as school libraries. They designed and calibrated sound-sensitive alert systems capable of automatically responding to excessive noise levels. Learning integrated the physics of sound waves and decibel measurement (Science), sensor-based programming and conditional logic (Technology), visual icon design for public awareness (Arts), and structural prototype development (Engineering). This intermediate project strengthened students' ability to integrate scientific inquiry, engineering design, computational thinking, and purposeful English communication through increasingly independent Head-On investigation, Hands-On engineering, and Minds-On collaborative problem-solving.

Grade 6 Module (Culminating): Earthquakes Shake the World: Building for Safety. The culminating module challenged students to investigate structural resilience under seismic conditions. Students explored the properties of seismic waves before designing, constructing, and testing earthquake-resistant architectural models equipped with multi-level sensor warning systems that responded to simulated ground movement. The module integrated seismic science and structural engineering (Science), sensor programming and automated warning systems (Technology), architectural modeling and prototype optimization (Engineering), and collaborative design communication (Arts). This culminating project required students to synthesize disciplinary knowledge, engineering design, computational thinking, and bilingual communication through increasingly sophisticated Head-On reasoning, Hands-On innovation, and Minds-On reflection and collaboration.

Additionally, the curriculum was systematically aligned with Taiwan's Grade-Level National Curriculum Guidelines and progressively incorporated bilingual scaffolds to support students' disciplinary learning and English language development through Triple-On project-based CLIL-STEAM pedagogy. As summarized in Table 1, the curriculum demonstrates a coherent progression of authentic engineering challenges, interdisciplinary STEAM integration, Triple-On learning processes, bilingual language supports, and intended learning outcomes across Grades 4–6. The complete curriculum frameworks for each grade are provided in Appendix A.

A defining feature of the curriculum was its integration of eco-conscious engineering practices, with recycled cardboard serving as the primary construction material for engineering prototypes (Fig. 2). Beyond its practical and environmental value, cardboard functioned as a physical semiotic resource that enabled students to externalize disciplinary thinking, negotiate design decisions, and communicate ideas through tangible artifacts. These multimodal opportunities also lowered communicative barriers for beginning English learners, creating accessible entry points for meaningful participation that helped sustain learners' confidence, motivation, and engagement throughout collaborative engineering activities.

Recycled cardboards as the primary instructional and learning materials

3.3 Research Context: Participants and the Research–Practice Partnership

The study was conducted in a public elementary school in southern Taiwan and followed a single cohort of students continuously from Grade 4 to Grade 6 over a three-year period. The final longitudinal sample comprised 89 students ($N = 89$) who completed the full three years of the curriculum and corresponding assessments. At the onset of the study, most participants demonstrated English proficiency between CEFR Pre-A1 and A1, representing typical beginning-level learners in Taiwanese public elementary schools.

Curriculum implementation was supported through a research-practice partnership involving three university researchers with expertise in bilingual education, science education, and science communication, together with one experienced elementary science teacher who served as the lead classroom instructor throughout the intervention. Instruction was delivered primarily in Mandarin Chinese to ensure conceptual understanding, with English systematically embedded through key disciplinary vocabulary, bilingual learning materials, coding interfaces, collaborative discussion, and presentation tasks. Rather than maximizing English exposure alone, the instructional design sought to encourage meaningful language use while maintaining learners' motivation and engagement in authentic disciplinary inquiry. Ethical approval was obtained from the appropriate institutional review board prior to data collection. Written parental consent and student assent were secured, and all data were anonymized before analysis.

3.4 Data Collection: A Multi-Source Longitudinal Archive

To capture the complexity of bilingual STEAM learning over time, the study constructed a longitudinal archive comprising multiple complementary data sources. Quantitative data consisted of school-administered English assessment mean scores collected at the end of each semester, providing six consecutive measures of students' English achievement across the three-year study period. These longitudinal assessment data served as the primary quantitative indicator for examining changes in English language proficiency over time (RQ1). Qualitative datasets comprised field notes and selective video recordings from 60 systematic classroom observation sessions; complete portfolios of students' physical and digital artifacts (e.g., cardboard prototypes, Micro:bit scripts, and Canva blueprints); transcripts of annual semi-structured student focus-group interviews; and ongoing teacher reflective journals. Collectively, these data provided rich evidence of learners' classroom participation, collaboration, multimodal meaning-making, communicative behaviors, and evolving perceptions of English use. They also offered insights into how learners' motivation and engagement were manifested and sustained through authentic disciplinary activities and collaborative bilingual learning experiences across the three-year curriculum.

3.5 Data Analysis

Qualitative data were analyzed using Braun and Clarke's (2006) reflexive thematic analysis to identify recurring patterns related to learners' motivation, engagement, participation, collaboration, multimodal meaning-making, learner agency, communicative practices, and responses to cognitive and linguistic challenges. Quantitative and qualitative findings were integrated through a convergent mixed-methods approach to explain how

students' developmental trajectories—and the processes through which motivation, engagement, and bilingual participation were sustained—emerged within the CLIL-STEAM learning ecology.

4. Results

This study employed a mixed-methods approach to examine students' developmental learning trajectories within a three-year project-based CLIL-STEAM curriculum. The following sections present quantitative evidence of students' English achievement, followed by qualitative findings that illuminate how learners' motivation, engagement, communicative participation, and learner agency evolved throughout the intervention. Together, the findings illustrate not only changes in language performance but also the developmental processes through which learners remained engaged in authentic bilingual disciplinary practices.

4.1 Quantitative Findings: Longitudinal Patterns of English Achievement

To address RQ1, quantitative analyses examined students' English achievement across six consecutive semesters over the three-year intervention. Semester-level English assessment scores were used to investigate longitudinal performance patterns during both non-intervention and CLIL-STEAM intervention semesters. Analyses proceeded from descriptive trends to within-student comparisons and longitudinal modeling to determine whether participation in the CLIL-STEAM curriculum was associated with measurable differences in English achievement.

4.1.1 Descriptive Trends Across Six Semesters

Descriptive statistics for students' semester-based English achievement across the six semesters are presented in Table 2. Overall, English performance remained relatively stable throughout the three-year period, although mean scores fluctuated across grades. Because the assessments were school-administered and differed somewhat in content emphasis and difficulty between semesters, the observed variation should be interpreted as developmental patterns rather than direct score progression.

Table 2
Semester English Achievement by Intervention Condition (N = 89)

Semester	Condition	Mean (M)	SD	Min	Max
111-1 (Grade 4, Sem 1)	Non-intervention	79.86	23.18	27.3	99.7
111-2 (Grade 4, Sem 2)	CLIL-STEAM intervention	83.78	20.56	30.0	100.0
112-1 (Grade 5, Sem 1)	Non-intervention	69.82	24.12	18.0	98.3
112-2 (Grade 5, Sem 2)	CLIL-STEAM intervention	74.04	22.44	29.8	97.3
113-1 (Grade 6, Sem 1)	Non-intervention	87.77	15.88	33.5	100.0
113-2 (Grade 6, Sem 2)	CLIL-STEAM intervention	87.29	15.59	42.0	100.0

4.1.2 Within-Grade Paired Contrasts

To examine changes within each academic year, paired-samples t-tests were conducted to compare students' performance between the non-intervention and CLIL-STEAM intervention semesters. As shown in Table 3, statistically significant improvements were observed during the intervention semesters in both Grade 4, $t(88) = 5.63$, $p < .001$, $d_z = 0.60$, and Grade 5, $t(88) = 6.11$, $p < .001$, $d_z = 0.65$. Approximately 73.0% of students demonstrated score gains in Grade 4, while 78.7% improved in Grade 5. In contrast, the difference observed in Grade 6 was small and not statistically significant, $t(88) = -0.87$, $p = .387$, $d_z = -0.09$.

Table 3
Within-Grade Paired Comparisons by Intervention Condition (N = 89)

Grade (Year)	Non intervention M (SD)	CLIL-STEAM Intervention M (SD)	Mean Diff.	t(df)	p	Cohen's d_z	% Improved
Grade 4 (111)	79.86 (23.18)	83.78 (20.56)	+ 3.92	5.63 (88)	< .001	0.60	73.0%
Grade 5 (112)	69.82 (24.12)	74.04 (22.44)	+ 4.22	6.11 (88)	< .001	0.65	78.7%
Grade 6 (113)	87.77 (15.88)	87.29 (15.59)	-0.48	-0.87 (88)	= .387	-0.09	43.8%

4.1.3 Composite Averages Across Three Years

To estimate the overall association of the intervention across the three-year period, each student's English scores were averaged separately across all non-intervention semesters and all intervention semesters (Table 4).

Table 4
Three-Year Composite English Achievement by Intervention Condition (N = 89)

Composite Index	Mean (M)	SD	Min	Max
Non-intervention average (111-1, 112-1, 113-1)	79.15	13.77	29.93	98.87
Intervention average (111-2, 112-2, 113-2)	81.83	13.44	39.00	98.60

Students recorded higher overall English scores during the CLIL-STEAM intervention semesters (M = 81.83, SD = 13.44) than during the corresponding non-intervention semesters (M = 79.15, SD = 13.77). This difference was statistically significant, $t(88) = 6.35$, $p < .001$, with a moderate within-subject effect size ($d_z = 0.67$).

Linear mixed-effects modeling with student as a random intercept and intervention condition and grade level as fixed effects converged with the paired comparisons: the model indicated an overall positive condition effect ($\$p < .001\$$) while revealing that the magnitude of difference varied across grade levels, with stronger advantages observed in Grades 4 and 5 than in Grade 6. Although the quantitative analyses primarily examined English achievement, these

results should be interpreted alongside the qualitative findings, which provide insights into how sustained motivation, engagement, and meaningful participation may have supported students' long-term language development within the CLIL-STEAM curriculum.

4.2 Qualitative Findings: Developmental Processes of Participation, Motivation, and Engagement in CLIL-STEAM Learning

The qualitative analysis drew on student focus group interviews, classroom observations, learning artifacts, and teacher reflective journals collected throughout the three-year CLIL-STEAM implementation. Through iterative thematic coding, six interrelated themes were identified and subsequently organized into three higher-order analytical categories. These categories capture how students entered, sustained, and ultimately transformed their learning experiences within a cognitively demanding bilingual STEAM environment. Rather than focusing solely on language outcomes, the qualitative findings illuminate the developmental processes through which learners' motivation, engagement, communicative participation, and learner agency evolved over time.

4.2.1 Category A: Engagement and Participation as the Entry Point to CLIL-STEAM Learning

This category examines how students initially accessed and sustained participation in the CLIL-STEAM curriculum. For novice bilingual learners operating under simultaneous cognitive and linguistic demands, engagement did not originate from language proficiency alone. Instead, learners' initial motivation to participate emerged from the material, collaborative, and purposeful design of classroom tasks. Hands-on artifact construction and peer collaboration functioned as entry conditions that enabled meaningful participation regardless of students' English levels, thereby preventing early disengagement and encouraging learners to remain willing to communicate despite limited English proficiency.

Theme 1: Hands-on, Minds-on Engagement as a Foundational Motivational Mechanism

Across all three grade levels, students consistently identified hands-on construction as the primary source of motivation and engagement. Rather than functioning merely as an instructional activity, hands-on engineering design provided learners with an immediate sense of purpose and accomplishment, encouraging them to participate actively despite the simultaneous cognitive and linguistic demands of the bilingual classroom. In contrast to conventional English classes which are often described as test-driven and repetitive, the CLIL-STEAM curriculum organized learning around the collective construction of functional artifacts. Whether students were programming a Micro:bit-controlled traffic light (Grade 4), designing a noise-detection system for public spaces (Grade 5), or engineering earthquake-resistant structures (Grade 6), the physical presence of a tangible object reoriented classroom participation from passive reception toward active problem-solving.

Longitudinal classroom observation logs recorded revealed that hands-on engagement frequently translated into sustained concentration and persistence. Rarely seen in their regular language or subject classes, students were often observed continuing to adjust circuits, reinforce cardboard structures, or debug code beyond designated class time. This pattern suggests that the Hands-On and Minds-On dimensions of the *Triple-On Learning Ecology* functioned together as motivational anchors that sustained learners' engagement, persistence, and willingness to communicate even when linguistic comprehension remained incomplete. Importantly, students who self-identified as having limited English proficiency demonstrated comparable levels of persistence when task goals were authentic, concrete, and visually meaningful.

Students' reflections further illuminated this contrast. One student recalled the excitement of the Grade 4 traffic light project as a step-by-step process culminating in a realistic traffic simulation, describing it as *"just like real life."*

XXXXXXXXXXXXXXXXXXXX, XXXXXXXXXXXXXXX, XXXXXXX, XXXXXXXX ("I remember when we first made the traffic light signaling simulation step by step in Grade 4 and then worked together with other groups for testing at the end of the semester, just like the real scenario in reality. Learning becomes so interesting, just like real life.") This reflection illustrates that students' initial motivation stemmed from authentic task participation rather than from language learning itself. The opportunity to construct tangible artifacts and simulate real-life situations transformed English into a meaningful tool for accomplishing shared disciplinary goals, thereby sustaining learners' engagement throughout the activity.

Another student highlighted the collective engagement during the earthquake project, noting that building and testing with recycled cardboard felt "like a science competition."

XXXXXXXXXXXXXXXXXXXXXXXXXXXX, XXXXXX, XXXXXXX, XXXXXX, XXXXXXXXXXX ("The most fun part was building the earthquake-detection structure with recycled cardboard. From brainstorming to testing, everyone was involved, step by step—it felt like a science competition.") Rather than emphasizing linguistic performance, the student highlighted collective participation, gradual problem solving, and shared accomplishment. These experiences appear to have fostered a sense of competence and belonging, both of which contributed to sustained engagement within the bilingual learning environment.

Crucially, hands-on engagement appeared to buffer linguistic frustration by shifting learners' attention from language accuracy to meaningful task completion. Instead of perceiving English as the primary obstacle, students increasingly viewed it as one of several resources that enabled successful engineering design and collaborative inquiry. The desire to complete and improve the artifact often outweighed the difficulty of English input. As one student explained, the difficulty of English became secondary when there was "something real to finish." XXXXXXXXXXX, XXXXXXXXXXX, XXXXXXXXXXXX, XXXXXXXXXXXX, XXXXXXX ("Although English was very hard, the fact that we had models to make, tasks to complete, and something real to finish made me not want to give up English. Just do it! That's it!")

Similarly, during the Grade 5 task, another student described actively seeking the meaning of English commands not for test performance, but to make the device function.

Micro:bit (When coding the Micro:bit to detect sound, I really wanted to know if it would light up. To make it light up, I had to look up what the English command meant. This is so different from memorizing English words for a test in the English class.) This quotation demonstrates that the learner's persistence was sustained not because English became easier, but because participation in a meaningful engineering task provided sufficient motivation to continue despite linguistic difficulty. Such findings suggest that authentic disciplinary purposes can reduce the discouraging effects of limited language proficiency while maintaining learners' willingness to participate.

Together, these findings suggest that embedding English within hands-on engineering challenges fundamentally changed students' orientation toward language learning. Rather than experiencing English as an abstract academic subject or a source of assessment anxiety, learners increasingly viewed it as a functional resource for solving problems, constructing artifacts, and collaborating with peers. Consequently, motivation and engagement were sustained not by simplifying linguistic demands but by increasing the authenticity and meaningfulness of classroom participation. This finding supports the proposition of the *Triple-On Learning Ecology* that participation can precede language proficiency because meaningful disciplinary activity encourages learners to remain engaged while their communicative competence gradually develops.

Theme 2: Peer Collaboration as Social Mediation for Sustaining Motivation and Participation

Video tracking data collected over the three-year intervention revealed consistent patterns of role differentiation within heterogeneous teams. Peer collaboration emerged as a second critical mechanism for sustaining learners' motivation, engagement, and meaningful participation throughout the CLIL-STEAM curriculum. Given the complexity of integrating engineering reasoning with English-mediated communication, participation rarely depended on individual language ability alone. Instead, learners remained engaged through collective problem-solving, shared responsibility, and mutual support, making participation a socially distributed process rather than an individual linguistic achievement. Classroom observations consistently showed students assuming complementary roles, such as engineer (model construction), designer (visual layout), and language broker (English–Chinese translation). This distribution of expertise enabled learners with different levels of English proficiency to contribute meaningfully without being marginalized, while simultaneously reducing the affective pressure associated with individual language performance. Rather than positioning spoken English as the sole indicator of participation, the collaborative task design created multiple legitimate pathways for disciplinary contribution. Through these shared learning experiences, students gradually developed confidence to participate, which in turn helped sustain their motivation and continued engagement despite ongoing linguistic challenges.

Students' reflective accounts further illustrate the importance of this socially mediated learning process. Several described relying on classmates to negotiate unfamiliar vocabulary, paraphrase instructions, or translate key ideas, emphasizing that peer support enabled successful task completion rather than merely correcting linguistic errors. One student explained: (My English is so bad. Whenever I came across words I couldn't say, my classmates always helped me so that we could complete the task together.) Rather than emphasizing linguistic deficiency, this reflection highlights how peer collaboration reduced learners' anxiety and enabled sustained participation in English-mediated activities. The student's willingness to remain engaged stemmed not simply from improved language ability, but from confidence that support was available when communication difficulties arose. In this way, collaborative interaction transformed language learning from an individual challenge into a shared accomplishment, allowing learners to participate actively while gradually developing both disciplinary understanding and communicative competence.

Importantly, peer assistance extended beyond simple translation or vocabulary explanation. Students strategically coordinated their linguistic and disciplinary strengths so that every group member could make a meaningful contribution to the final task. This collaborative organization redistributed communicative responsibility while maintaining high levels of participation and shared ownership of learning. One student explained: (We divided and shared the work—I spoke in Chinese, and my teammate helped translate into English because both languages were important for helping everyone understand. In this way, we were able to complete our poster and deliver a successful presentation together.) This quotation illustrates that learners viewed bilingual communication as a collective rather than individual responsibility. By combining complementary strengths, students experienced English as a practical communicative resource for achieving shared disciplinary goals rather than as an obstacle to participation. Such experiences appeared to reinforce both learners' motivation to participate and their willingness to communicate within the bilingual classroom.

A Grade 6 student's reflection on the final earthquake project further illustrates how collaborative participation enabled learners with different strengths to contribute meaningfully. Although the student experienced considerable anxiety about speaking English publicly, the group intentionally distributed responsibilities according to members' disciplinary expertise and communicative confidence. This flexible organization allowed every learner to participate in ways that matched individual strengths while remaining actively involved in the shared task. Micro:bit (I was responsible for the programming because I was good at using the Micro:bit. Although I was anxious about speaking English, my teammates presented most of the explanation while I demonstrated the model and spoke a few sentences. I still felt that my contribution mattered because we worked as a team.) Rather than withdrawing because of linguistic anxiety, the student remained an active contributor through alternative yet equally valued forms of participation. Programming the Micro:bit, demonstrating the engineering prototype, and delivering brief English explanations enabled the learner to experience competence and group membership despite limited oral production. This example suggests that learners' motivation did not simply arise from increased linguistic confidence; rather, it developed through meaningful contribution, recognition from peers, and successful participation in authentic disciplinary activity.

Viewed through a sociocultural lens, these collaborative arrangements resemble learners operating within the Zone of Proximal Development (Vygotsky, 1978), where cognitive and linguistic challenges were negotiated through shared activity. By legitimizing multiple forms of contribution and distributing expertise across group members, peer collaboration prevented English proficiency from becoming the sole criterion for successful participation. Instead,

participation was grounded in collective problem-solving, mutual support, and authentic disciplinary goals. These socially mediated experiences not only scaffolded language development but also strengthened learners' sense of competence and belonging, thereby sustaining motivation, engagement, and willingness to communicate. Together, these findings further support the central proposition of the *Triple-On Learning Ecology*: peer collaboration served as the social mechanism that transformed individual linguistic limitations into collective communicative resources, enabling motivation and engagement to emerge through meaningful participation in authentic disciplinary practice.

4.2.2 Category B: Mediating Linguistic Challenges through Purpose and Multimodality

The second category captures how students navigated persistent linguistic challenges within the CLIL-STEAM environment. Rather than eliminating language anxiety, the curriculum reconfigured its role in the learning process. Focus group transcripts revealed that although evaluative language anxiety remained evident throughout the intervention, students continued to participate actively in oral communication during the class exhibitions. Through purposeful communication and multimodal expression, linguistic difficulty became a manageable aspect of participation rather than an obstacle to it. Authentic tasks and expanded semiotic resources shifted learners' attention from linguistic accuracy toward communicative purpose, thereby sustaining motivation, engagement, and willingness to communicate despite ongoing linguistic uncertainty.

Theme 3: Persistent Language Anxiety Reframed through Purposeful Communication

Despite the supportive and collaborative classroom environment, many students continued to report anxiety about using English, particularly during oral production and class presentations. The thematic analysis suggests that this anxiety was not primarily rooted in classroom interaction itself, but rather in a broader, socially constructed perception of English as a standardized and evaluative subject. Within the Taiwanese EFL context, English is frequently associated with native-like pronunciation, linguistic correctness, and public evaluation, even at the elementary level. Nevertheless, students consistently demonstrated a willingness to participate in English-mediated activities despite these concerns, suggesting that linguistic anxiety no longer functioned as the primary determinant of classroom participation. One student expressed this tension succinctly: *I'm always worried that I'll mispronounce English words, that my pronunciation isn't accurate enough, and that I'll embarrass myself. But because I want to complete the task, I still try my best to express my ideas and share them with others.* This quotation illustrates that learners' anxiety remained genuine, yet it no longer dictated whether they chose to communicate. Instead, authentic disciplinary goals provided a meaningful reason for students to use English despite continued uncertainty. Rather than waiting until they felt linguistically confident, students gradually developed confidence through repeated experiences of purposeful participation.

A second theme emerging from the interviews was learners' appreciation of bilingual communication as a legitimate and supportive way of participating. Several students expressed a preference for using both Chinese and English during presentations and collaborative discussions. *I'd feel happier and more comfortable if oral presentations could be delivered partly in Chinese and partly in English.* Rather than viewing Chinese as an obstacle to English learning, students perceived the two languages as complementary communicative resources. Chinese enabled learners to negotiate ideas, clarify disciplinary concepts, and support one another, whereas English functioned as the language for targeted learning for communication and sharing project outcomes with wider audiences. Within this CLIL-STEAM learning ecology, both languages were welcomed, valued, and respected because each contributed to meaning-making, collaboration, and successful disciplinary communication. This multilingual orientation reduced communicative pressure while allowing learners to draw flexibly on their full linguistic repertoire to accomplish authentic disciplinary tasks.

A further nuance emerged from the interview data: authentic communicative purpose gradually outweighed learners' concern about linguistic accuracy. This shift became particularly evident during the earthquake preparedness project, where students perceived their presentations as opportunities to educate others rather than simply complete an English assignment. *Although I did not enjoy English class and felt uncomfortable speaking English, I was willing to try because this design project was meant to help others understand earthquake safety.*

Rather than avoiding English because of fear, the student chose to communicate because the project carried authentic social value. Helping others became a more powerful source of motivation than avoiding linguistic mistakes. As communicative purpose became increasingly meaningful, learners shifted their attention away from producing perfect English toward successfully conveying disciplinary ideas that could benefit others.

Similarly, a fifth-grade student described how successful communication during a public poster presentation gradually reduced performance anxiety. *I knew my English might not be correct and my grammar could be wrong, but I felt our noise alert design was really important because it reminds people to be quiet in public spaces. I wanted others to understand why it worked. When I saw them understand and nod, I wasn't so nervous anymore.* This quotation illustrates a subtle yet important transformation in learners' communicative orientation. Success was no longer judged primarily by grammatical accuracy, but by whether the intended message was understood. Audience comprehension and positive responses provided immediate evidence that meaningful communication had occurred, reinforcing learners' confidence, sustaining their motivation, and encouraging continued participation despite ongoing linguistic limitations.

Taken together, these findings suggest that language anxiety was not eliminated within the CLIL-STEAM curriculum; instead, its role in learning was fundamentally reconfigured. Authentic disciplinary tasks, multimodal artifacts, and the flexible use of both Chinese and English redirected learners' attention from linguistic perfection toward meaningful communication, collaborative problem-solving, and civic contribution. Within this multilingual learning ecology, all languages were welcomed, valued, and respected as legitimate resources for meaning-making, collaboration, and disciplinary learning, rather than being positioned in competition with one another. Consequently, learners increasingly perceived English not as an object of evaluation, but as one component of a broader communicative repertoire for addressing authentic disciplinary problems. These findings further support the central proposition of the *Triple-On Learning Ecology* that motivation, engagement, and willingness to communicate emerge through meaningful participation, while linguistic confidence develops progressively through repeated experiences of authentic communication.

Theme 4: Multimodal Expression as a Resource for Deeper Meaning-Making

This CLIL-STEAM curriculum's deliberate integration of multimodality including visual design, physical modeling, digital tools, and coding provides a critical Minds-On bridge for learners whose conceptual understanding exceeded their English expressive capacity. Rather than serving as supplementary illustrations, multimodal artifacts functioned as epistemic and communicative resources that enabled students to externalize disciplinary reasoning and participate meaningfully despite linguistic limitations. By expanding legitimate pathways for expression, multimodal resources reduced communicative barriers while sustaining learners' motivation, engagement, and willingness to communicate throughout the bilingual inquiry process.

For many students, multimodal resources enabled them to demonstrate disciplinary understanding beyond what they could express verbally in English. Classroom observations showed that learners actively coordinated multiple semiotic resources, including images, physical models, gestures, symbols, digital media, and limited English text, to construct and communicate meaning. In Lin's (2019) terms, students continually trans-semiotized, moving fluidly across different representational modes as communicative demands evolved. Rather than functioning as supplementary illustrations, cardboard models, design sketches, and visual artifacts became legitimate means of disciplinary communication. As one student explained: *“My English is so bad, and I can't write English sentences. But in this class I discovered that I could use cardboard models, design drawings, and colors to help others understand my ideas.”* Rather than perceiving limited English proficiency as a barrier, the learner recognized multiple semiotic resources as equally legitimate means of communication. Participation therefore became possible through the coordinated use of visual, material, and linguistic resources rather than English alone.

The digital design component further expanded opportunities for participation by distributing communicative agency across group members. *“We used Canva to design the poster together. Besides English, we could also choose fonts, icons, symbols, and pictures to present our ideas. It was really fun.”* Collaborative digital design enabled students to co-construct meaning through images, layout, symbols, and concise English text. Communication therefore became a genuinely collaborative process rather than an individual linguistic performance. Learners with different strengths could contribute through visual design, technological skills, organization, or English expression, creating a more inclusive communicative environment in which every member could participate meaningfully.

Students also recognized that multimodal artifacts often communicated ideas more effectively than spoken language alone. *“I think showing the model directly is much easier and clearer than explaining everything with words.”* Another student similarly reflected: *“Our poster included meaningful symbols and diagrams, together with key English words, so people could immediately understand what we wanted to explain.”*

Together, these reflections suggest an important shift in learners' communicative orientation. Students no longer evaluated successful communication solely according to spoken English or grammatical accuracy. Instead, meaning-making became the primary objective, with visual representations, physical artifacts, and selected English expressions working together to convey disciplinary ideas effectively.

A fifth-grade student further illustrated how multimodal communication compensated for temporary lexical gaps during classroom interaction. *“At that time I didn't know how to say ‘vibration’ in English, so I drew a wave-like picture and pointed to the changing lights on the Micro:bit. Both my teacher and classmates understood me. That's when I realized I could use drawing to explain my ideas too.”*

This quotation illustrates how multimodal meaning-making transformed temporary linguistic limitations into successful communication without interrupting participation. Instead of withdrawing because of lexical gaps, the learner strategically coordinated drawings, gestures, technological artifacts, and limited English to express disciplinary understanding. Experiencing communicative success in this way strengthened self-efficacy, reinforced motivation, and encouraged continued willingness to participate in increasingly challenging bilingual tasks.

Collectively, these findings demonstrate that multimodal artifacts functioned not merely as instructional supports but as legitimate communicative resources within the CLIL-STEAM classroom. By recognizing multiple modes of meaning-making, the curriculum ensured that limited English proficiency did not equate to limited disciplinary understanding or reduced classroom participation. Instead, multimodal communication enabled learners to experience success before achieving complete linguistic mastery, thereby strengthening confidence while sustaining motivation and engagement.

From the perspective of the *Triple-On Learning Ecology*, multimodal mediation served not only as cognitive scaffolding but also as a motivational mechanism that connected Hands-On exploration, Minds-On meaning-making, and Head-On communication. Rather than positioning English as the sole vehicle for demonstrating knowledge, the curriculum encouraged learners to orchestrate language, visual representation, physical artifacts, digital media, and embodied action as complementary communicative resources. In doing so, meaningful participation became accessible to all learners, allowing motivation, engagement, and communicative confidence to develop progressively through authentic disciplinary inquiry.

4.2.3 Category C: Identity, Agency, and Civic Meaning-Making beyond the Classroom

The third category captures a progressive transformation in how students understood learning, English, and their own identities as learners throughout the three-year CLIL-STEAM curriculum. As they engaged in transdisciplinary projects addressing authentic civic issues, learning evolved from completing school-based tasks to designing solutions for real audiences and real-world problems. Within this process, English was increasingly perceived not as an isolated academic subject but as a functional communicative resource for expressing ideas, collaborating with others, and contributing to the community. Consequently, learners began to develop identities characterized by greater agency, responsibility, and civic awareness. This developmental process also reflected a qualitative shift in motivation and engagement—from fulfilling classroom requirements toward participating purposefully in meaningful communication that extended beyond the classroom.

Theme 5: Transdisciplinary Learning as a Civic Meaning-Making Process

A defining feature of the CLIL-STEAM curriculum was its transdisciplinary orientation, through which students experienced learning not as compartmentalized school subjects, but as integrated responses to authentic community issues. Across the three-year curriculum, projects addressing traffic safety, noise pollution, and earthquake preparedness positioned learners as problem-solvers rather than knowledge receivers. These authentic contexts extended learning beyond classroom requirements and provided meaningful reasons for students to communicate, thereby sustaining their motivation, engagement, and willingness to participate in bilingual disciplinary inquiry.

Interview data revealed a clear shift in how students evaluated the purpose of their work. Rather than viewing artifacts as products created primarily for teacher assessment, students increasingly described them as resources intended to inform, assist, and communicate with real audiences. One student noted: *“Our project wasn’t just something to submit for a grade. We worked together to solve a real-world problem, and what we created could actually help people in everyday life.”* This reflection illustrates an important transformation in learners’ understanding of communication. The intended audience shifted from the teacher to the wider community, suggesting that successful communication was increasingly evaluated according to its usefulness and social impact rather than academic performance alone. As classroom communication became more authentic, learners also demonstrated stronger motivation to make their ideas understandable to others.

Similarly, students also began to perceive English as part of meaningful civic communication rather than simply another school subject. *“We learned to use design to help people understand earthquake precautions. I think this kind of class is more useful.”* Rather than communicating merely to fulfill classroom requirements, students used English to explain ideas that they believed could benefit others. Helping community members understand earthquake preparedness provided a meaningful communicative purpose that outweighed concerns about linguistic accuracy. In this way, English became a functional resource for civic engagement rather than simply an object of language learning.

This sense of civic responsibility became particularly evident during projects requiring students to investigate issues within their own communities. In the Grade 4 traffic safety project, learners measured pedestrian crossing times outside their school and incorporated these data into programmable traffic signaling systems. As one student explained: *“We actually measured and recorded how many seconds people needed to cross the road outside our school and coded the results into the program. Because it was something that affected our daily lives, we spent a long time discussing it. We also wanted our worksheets and posters to be very clear because we were worried people might not understand.”* Rather than completing a hypothetical classroom exercise, students designed solutions for real users within their own community. Authentic data collection, engineering design, and bilingual communication became mutually reinforcing processes. Learners carefully refined both their designs and their English explanations because they viewed audience understanding as an essential part of responsible design. This concern for communicative clarity reflects an emerging awareness that successful engineering solutions require not only technical feasibility but also effective public communication.

Collectively, these accounts reveal a developmental progression from completing school tasks toward assuming socially responsible identities as communicators, designers, and problem-solvers. Students increasingly recognized that successful inquiry required more than disciplinary knowledge; it also demanded empathy, audience awareness, communicative clarity, and consideration of social impact. The transdisciplinary curriculum encouraged learners to integrate engineering feasibility, scientific reasoning, visual communication, and bilingual expression in ways that served authentic public audiences.

Importantly, English was no longer experienced as an isolated academic subject but as one component of a broader communicative repertoire for engaging with real-world issues. Through repeated participation in socially meaningful inquiry, learners developed greater agency as they came to view themselves as contributors whose ideas could inform, support, and influence others. From the perspective of the *Triple-On Learning Ecology*, authentic civic purpose functioned as the driving force that connected Hands-On inquiry, Minds-On meaning-making, and Head-On communication, sustaining learners’ motivation, engagement, and willingness to communicate throughout increasingly complex bilingual learning experiences.

Theme 6: Repositioning English as a Functional Tool for Real-World Communication

The final and perhaps most transformative theme concerned students’ evolving perceptions of English and their identities as English users. Across the three-year curriculum, learners gradually shifted from viewing English as an academic subject to be studied toward understanding it as a practical communicative resource for solving problems, collaborating with others, and sharing ideas beyond the classroom. This evolution reflected not only changing perceptions of language itself but also a broader transformation in learners’ motivation, engagement, and willingness to communicate through English.

A major catalyst for this transformation was the authentic integration of English into disciplinary practice. Rather than being taught as isolated linguistic content, English became the language needed for meaningful action—interpreting Micro:bit interfaces, understanding programming commands, labeling engineering designs, and communicating project outcomes. As one student noted: *“Even though the Micro:bit interface is entirely in English and very difficult to understand, it made me realize how important English is in many different fields in real life.”* Although the learner acknowledged the challenges of working with English-language technology, the experience also revealed English as an authentic disciplinary resource rather than merely another school subject. Instead of diminishing motivation, these technological demands strengthened students’ appreciation of English as a tool for future learning and participation in broader scientific and technological communities.

Repeated engagement in authentic disciplinary tasks gradually reshaped students’ understanding of why English mattered. Another student reflected on the earthquake preparedness project: *“I used to think English was only for exams. But in this class, we used English to tell people how to protect themselves during an earthquake. I realized that English is an international language that helps people communicate, not just something for tests.”* Rather than defining English through examinations, the learner increasingly associated it with communication, collaboration, and helping others understand important information. English therefore acquired personal relevance because it enabled

meaningful interaction rather than because it was formally assessed. This represents a significant shift from extrinsic academic expectations toward intrinsically meaningful communication.

The contrast with students' after-school cram school (buxiban) experiences further underscored the different perception of English :
“At after-school cram school, we mostly memorize vocabulary and completed worksheets and test papers. But in this class, if I don't understand the English instructions and missed something, my robot won't move. So I actively ask my classmates for help. The English for this class is really 'alive.'” The student's description of English as “alive” captures a profound change in learning experience. Language was no longer encountered as decontextualized knowledge to be memorized but as a living resource embedded within meaningful disciplinary practice. Because communication directly influenced the success of engineering tasks, learners actively sought English rather than passively receiving it, demonstrating greater agency, engagement, and willingness to communicate.

Collectively, these reflections reveal a fundamental transformation in learners' identities. English was no longer experienced as a gatekeeping academic subject but as an enabling communicative resource for participation, collaboration, innovation, and civic engagement. Students increasingly perceived themselves not simply as learners of English but as emerging bilingual communicators capable of using English to explain ideas, solve authentic problems, and contribute to their communities.

Within the *Triple-On Learning Ecology*, learners' evolving identities emerged through sustained participation in authentic disciplinary practices. Hands-On inquiry created meaningful contexts for communication; Minds-On engagement deepened disciplinary understanding; and Head-On challenges provided authentic reasons to communicate with real audiences. Consequently, English became not merely a subject to master but a practical resource for participating meaningfully in authentic disciplinary and civic contexts. Rather than waiting until they felt sufficiently proficient in English, students gradually developed confidence, motivation, and communicative agency through repeated experiences of purposeful bilingual participation. Ultimately, the most significant change was not simply that students learned more English, but that they increasingly saw themselves as bilingual communicators capable of using English, together with disciplinary knowledge and multimodal resources, to contribute meaningfully to their communities.

4.3 Summary of Results

Taken together, the qualitative findings depict a coherent CLIL-STEAM learning ecology structured by task materiality, social mediation, and purposeful communication. Rather than progressing through a linear accumulation of linguistic knowledge, students developed adaptive participation strategies that enabled sustained meaning-making and communication under conditions of considerable cognitive and linguistic challenge. Across the three-year curriculum, learners' motivation and engagement were gradually cultivated through authentic participation in engineering design, collaborative inquiry, multimodal communication, and socially meaningful problem-solving, rather than through increasing language proficiency alone.

As summarized in Table 5, the six themes converge into three analytically distinct yet developmentally connected categories. Students first gained access to bilingual learning through hands-on engagement and collaborative participation (Category A), then navigated persistent linguistic challenges through purposeful communication and multimodal mediation (Category B), and ultimately reconceptualized English as a functional resource for civic communication, learner agency, and social responsibility (Category C). Across these three categories, motivation and engagement evolved alongside participation rather than preceding it, suggesting that authentic disciplinary activity provided the conditions through which learners remained willing to communicate despite continuing linguistic uncertainty.

Table 5
Qualitative Findings in the Triple-On Learning Ecology

Key Themes	Core Learning Pattern Identified	Salient Student Experiences	Dominant Mediating Processes (Triple-On)	Learning Function within the Ecology
Category A				
Engagement and Participation as Initial Access to Learning				
Theme 1: Hands-on, minds-on engagement Theme 2: Peer collaboration as cognitive and affective scaffolding	Students gained initial motivation and sustained engagement through authentic hands-on participation and collaborative learning rather than linguistic proficiency alone.	• Hands-on construction anchored attention and persistence • Peer roles enabled participation despite limited English • Task completion outweighed fear of language difficulty	Hands-On Task material artifacts as cognitive anchors + Minds-On Distributed roles, Peer-mediated support, Collaborative problem-solving	Enabled initial access to cognitively demanding CLIL-STEAM tasks by fostering motivation, lowering participation barriers, and redistributing communicative responsibility.
Category B				
Mediating Linguistic Challenges through Purposeful Communication and Multimodality				
Theme 3: Anxiety reframed through purposeful communication Theme 4: Multimodal expression as epistemic support	Linguistic difficulty remained present but became manageable as authentic communicative purposes and multimodal resources sustained learners' motivation, engagement, and willingness to communicate.	• Anxiety shifted from avoidance to tolerable risk • Meaning prioritized over grammatical accuracy • Visual, material, and digital modes compensated for lexical gaps	Head-On Authentic problem-solving task and communicative demand + Minds-On Multimodal and trans-semiotic meaning-making	Sustained motivation and meaningful participation under cognitive-linguistic challenge by expanding communicative resources beyond language alone.
Category C				
Identity, Agency, and Civic Meaning-Making				
Theme 5: Transdisciplinary learning as civic engagement Theme 6: English repositioned as a functional communicative tool	Students developed increasingly agentic learner identities by recognizing English as a meaningful communicative resource for civic participation and real-world problem-solving.	• Learning oriented toward real audiences • Design decisions integrated science, visuals, and language • English perceived as "alive" and instrumental	Hands-On + Minds-On + Head-On Integrated learning ecology, public audience and communicative responsibility	Supported the development of learner identity, agency, sustained motivation, and authentic communicative engagement by connecting English with meaningful civic participation.

Viewed collectively, the three categories also reveal a clear developmental trajectory from participation, to communication, and ultimately to identity. Initial engagement was established through hands-on participation and peer collaboration; communicative confidence was subsequently strengthened through purposeful communication and multimodal meaning-making; and, over time, learners increasingly developed agentic identities as bilingual communicators capable of contributing to authentic disciplinary and civic contexts. Rather than representing isolated themes, these findings illustrate an interconnected developmental process through which participation gradually evolved into communicative competence, learner agency, and meaningful civic engagement.

Accordingly, the primary contribution of the CLIL-STEAM curriculum lies not in accelerating short-term gains on standardized English assessments, but in cultivating a resilient bilingual learning ecology in which English functions as an enabling resource for participation, motivation, engagement, learner agency, and socially meaningful communication. Viewed through the *Triple-On Learning Ecology*, authentic disciplinary participation created the conditions under which learners remained willing to communicate despite continuing linguistic uncertainty, allowing communicative confidence, learner identity, and bilingual competence to develop progressively over time. These findings suggest that meaningful participation is not merely an outcome of language learning, but a foundational mechanism through which motivation, engagement, learner agency, and bilingual development can be sustained within transdisciplinary CLIL-STEAM education. This ecological interpretation provides the foundation for the following discussion, which examines how motivation, engagement, multimodal mediation, and identity transformation collectively reshape what counts as meaningful progress in bilingual STEAM education.

5. Discussion

This study examined bilingual learning within a three-year CLIL-STEAM curriculum through three complementary questions concerning students' language development (RQ1), learning experiences (RQ2), and the pedagogical processes through which project-based, multimodal, collaborative, and transdisciplinary

practices mediated these experiences (RQ3). Although the research questions addressed different dimensions of learning, the mixed-methods findings suggest that they are best interpreted as interconnected components of a single developmental process.

The quantitative results revealed modest but relatively stable patterns of English achievement across the three-year period, whereas the qualitative findings documented substantial changes in students' motivation, engagement, participation, communicative practices, learner agency, and perceptions of English. This divergence does not necessarily indicate inconsistency between the two forms of evidence. Rather, it suggests that bilingual development in CLIL-STEAM cannot be understood solely through formal measures of linguistic proficiency. Students' development was also reflected in their increasing capacity to remain engaged in cognitively demanding tasks, collaborate through multilingual and multimodal resources, communicate despite linguistic uncertainty, and use English for disciplinary and civic purposes.

Taken together, the findings indicate that bilingual learning developed through a reciprocal relationship among participation, motivation, engagement, communication, and learner identity. Students did not necessarily become motivated because they had first achieved sufficient English proficiency. Instead, meaningful participation in authentic disciplinary practices appeared to generate the motivation, confidence, and communicative agency necessary for continued bilingual learning. Building on this interpretation, the discussion advances the *Triple-On Learning Ecology* as a process-oriented explanation of how motivation, engagement, participation, multimodal mediation, and bilingual development co-evolved within the CLIL-STEAM curriculum.

5.1 Bilingual Development as an Ecological Rather than Linear Process (RQ1)

The first proposition concerns how bilingual development should be interpreted in relation to RQ1. Although students demonstrated only modest gains in school-based English assessments, this pattern should not be viewed simply as evidence of limited instructional effectiveness. The relatively stable scores may instead reflect a period of consolidation and reorganization within an increasingly demanding interdisciplinary curriculum. As the curriculum progressed, students had to coordinate scientific reasoning, engineering design, technological operation, collaborative problem-solving, multimodal representation, and English-mediated communication. Their cognitive and attentional resources were therefore distributed across multiple simultaneous demands rather than concentrated exclusively on vocabulary, grammar, or test performance. Students were not merely acquiring additional linguistic knowledge; they were also learning to use existing English resources strategically within increasingly complex disciplinary practices.

The findings consequently suggest a potential construct mismatch between what conventional school-based assessments measured and what the curriculum actually developed. Formal assessments primarily captured discrete linguistic knowledge and decontextualized performance, whereas the CLIL-STEAM curriculum cultivated broader competencies, including sustained engagement, collaborative communication, multimodal meaning-making, disciplinary reasoning, and strategic language use in authentic contexts. These developments may not have been fully visible in achievement scores. The stable proficiency trajectory therefore does not necessarily represent stagnation, but may indicate that students maintained their language performance while expanding their communicative, disciplinary, motivational, and participatory capacities.

Bilingual development in this context was thus not characterized by continuous and uniform score increases. Instead, it involved alternating phases of participation, consolidation, experimentation, communicative risk-taking, and gradual reorganization. This pattern suggests that bilingual development in CLIL-STEAM is better understood as ecological rather than linear. Linguistic growth emerged through interaction with disciplinary complexity, social participation, multimodal mediation, and authentic communicative purpose. Progress was therefore reflected not only in how much English students knew, but also in how flexibly, persistently, and purposefully they could mobilize the linguistic and multimodal resources available to them.

5.2 Meaningful Participation as a Developmental Driver of Motivation and Proficiency (RQ2)

The second proposition addresses students' learning experiences in relation to RQ2. The qualitative findings consistently indicate that meaningful participation preceded measurable language growth. Rather than waiting until they possessed sufficient English proficiency or confidence, students developed motivation, communicative confidence, and willingness to communicate through repeated engagement in authentic disciplinary tasks. Hands-on engineering activities, such as constructing traffic-control systems, programming Micro:bit applications, and designing earthquake-preparedness solutions, created concrete communicative needs that extended beyond conventional language practice. English became meaningful because it enabled students to interpret technological interfaces, explain designs, collaborate with peers, and communicate project outcomes.

These findings suggest that motivation should not be conceptualized solely as a prerequisite for learning. Instead, motivation and participation developed reciprocally through authentic disciplinary activity. Each successful experience of contributing to a group, solving a problem, or communicating ideas despite linguistic uncertainty reinforced learners' confidence and encouraged continued engagement. Participation therefore functioned not merely as a behavioral outcome but as the experiential condition through which learners repeatedly encountered English in meaningful contexts, experimented with emerging communicative strategies, and gradually expanded their communicative competence. At the same time, learners' own language ideologies can constrain participation even where multilingual resources are pedagogically available, with students internalizing monolingual norms about what counts as legitimate classroom language (Kim & Kim, 2024).

This interpretation extends current understandings of CLIL by suggesting that authentic disciplinary participation constitutes a developmental mechanism rather than simply a pedagogical strategy. Participation is not merely the consequence of language proficiency but one of its principal drivers. Meaningful engagement in authentic tasks sustained learners' motivation long enough for communicative confidence and bilingual competence to emerge progressively over time, supporting an ecological view of language development in which participation, motivation, and proficiency evolve reciprocally rather than sequentially.

5.3 Multimodal and Collaborative Mediation as Conditions for Bilingual Learning (RQ2 + RQ3)

The third proposition explains how project-based, multimodal, and collaborative practices mediated bilingual learning in relation to RQ2 and RQ3. Rather than relying exclusively on spoken or written English, students coordinated meaning-making across physical models, diagrams, digital technologies, coding interfaces, gestures, peer interaction, Chinese, and emerging English resources. These multimodal artifacts functioned not merely as instructional supports but as epistemic tools that enabled learners to externalize ideas, represent disciplinary reasoning, and sustain communication despite linguistic limitations. Similarly, peer collaboration distributed expertise across group members, allowing students to contribute through complementary strengths in programming, design, construction, organization, translation, and oral explanation. Participation therefore depended less on individual language proficiency than on the coordinated use of multiple communicative resources.

These findings support an ecological conceptualization of bilingual competence. Within the CLIL-STEAM classroom, successful participation emerged through interactions among learners, disciplinary tasks, artifacts, technologies, languages, and other semiotic resources rather than through independent language performance alone. Although language anxiety remained, authentic communicative purposes shifted learners' attention from speaking accurately to making ideas understandable, while multimodal resources and peer support reduced the communicative risks associated with limited English.

The findings therefore suggest that multimodal mediation and collaboration do more than facilitate bilingual learning; they fundamentally reorganize the conditions under which motivation, engagement, and communication become possible. By expanding legitimate forms of participation beyond spoken English alone, learners were able to contribute meaningfully before attaining full linguistic proficiency. Such experiences progressively strengthened communicative confidence, willingness to communicate, and learner agency, reinforcing the ecological view that bilingual competence develops through the dynamic coordination of disciplinary participation, multimodal mediation, and authentic communication rather than through language acquisition alone.

5.4 From Participation to Communicative and Civic Identity

A fourth proposition emerging from the findings concerns learner identity. Across the three-year curriculum, students gradually shifted from viewing themselves as learners completing school assignments to seeing themselves as communicators, designers, problem-solvers, and contributors capable of addressing authentic community issues. This development was particularly evident in projects related to traffic safety, noise pollution, and earthquake preparedness, where students were required to integrate scientific reasoning, engineering design, multimodal representation, and bilingual communication for real audiences. Within this process, English was increasingly repositioned from an academic subject to a functional communicative resource used alongside Chinese, visual representations, physical models, gestures, and digital technologies.

This transformation was not only communicative but also motivational. As students recognized that their ideas could inform, assist, or benefit others, participation acquired greater personal and civic significance. Motivation became increasingly connected to authorship, responsibility, and social contribution rather than merely completing classroom tasks or meeting teacher expectations. English therefore derived its value from what it enabled learners to accomplish within authentic disciplinary and community contexts rather than from its role as an assessed school subject.

Identity development can thus be understood as the culmination of the developmental trajectory identified throughout the study: *Participation* → *Communication* → *Identity*. Hands-on participation enabled learners to enter bilingual disciplinary activity, purposeful multimodal communication supported successful interaction despite linguistic limitations, and repeated experiences of meaningful participation gradually fostered more agentic identities as bilingual communicators. The most enduring outcome of the curriculum was therefore not simply improved language performance but a transformed perception of English as a resource for disciplinary inquiry, civic participation, and meaningful communication.

5.5 The Triple-On Learning Ecology as a Process-Oriented Theory of CLIL-STEAM Learning

Taken together, the findings extend beyond the evaluation of a single curriculum and contribute a broader theoretical perspective on bilingual STEAM learning. Rather than conceptualizing CLIL as a linear relationship between instructional input and language outcomes, this study proposes the *Triple-On Learning Ecology* as a process-oriented explanation of how bilingual development unfolds through sustained disciplinary participation. Within this ecology, Hands-On engagement provides material and experiential access to disciplinary inquiry, Minds-On engagement mediates conceptual understanding through collaborative and multimodal meaning-making, and Head-On engagement creates authentic cognitive, communicative, and civic challenges that give language learning meaningful purpose. Rather than functioning as separate stages, these three dimensions operate reciprocally to support increasingly sophisticated forms of bilingual participation.

The *Triple-On Learning Ecology* also offers a different interpretation of the relationship among motivation, engagement, participation, and bilingual development. Motivation is not treated as a prerequisite for participation but as a dynamic outcome continually renewed through meaningful disciplinary activity. Engagement represents the sustained process through which learners remain involved in cognitively demanding tasks, while participation serves as the developmental mechanism through which communicative confidence, learner agency, and bilingual competence gradually emerge. By integrating material activity, multimodal mediation, collaborative inquiry, and authentic communicative purpose, the framework explains how learners can participate successfully despite incomplete linguistic proficiency.

This ecological perspective helps explain why qualitative transformation may precede measurable language gains during the early stages of bilingual education. More importantly, it reframes meaningful participation not simply as an outcome of bilingual learning but as the foundational mechanism through which motivation, engagement, learner identity, and bilingual communicative competence co-develop over time. As such, the Triple-On Learning Ecology

provides a process-oriented framework for understanding and designing CLIL-STEAM environments that promote sustained bilingual learning through authentic disciplinary practice.

6. Conclusion

Learning another language is often imagined as climbing a ladder—one word, one sentence, and one proficiency level at a time. The findings of this study suggest a different metaphor. Within the CLIL-STEAM classroom, bilingual learning resembled the gradual development of an ecosystem rather than the ascent of a ladder. Students did not wait until their English was “good enough” before participating. Instead, through designing, building, discussing, presenting, and solving authentic disciplinary problems together, they gradually found meaningful reasons to communicate. As participation deepened, so too did their motivation, engagement, communicative confidence, and willingness to use English.

This developmental process is conceptualized through the *Triple-On Learning Ecology*, in which Hands-On, Minds-On, and Head-On engagement function as complementary and mutually reinforcing dimensions of bilingual learning. Hands-On engagement grounds learning in authentic disciplinary practice, Minds-On engagement supports collaborative and multimodal meaning-making, and Head-On engagement provides the cognitive and communicative challenges that make language use purposeful. Rather than operating sequentially, these dimensions interact dynamically to create conditions in which learners can participate meaningfully despite incomplete linguistic proficiency. In this ecology, participation becomes the mechanism through which communication, motivation, learner agency, and bilingual competence gradually co-develop.

The findings therefore suggest that meaningful participation should be viewed not simply as an outcome of bilingual learning but as one of its primary developmental drivers. This perspective reframes bilingual education by shifting attention from how much English learners know to how purposefully they are able to use English to think, collaborate, communicate, and contribute within authentic disciplinary and civic contexts. By proposing the *Triple-On Learning Ecology* as a process-oriented framework, this study offers a theoretical account of how motivation, engagement, participation, and learner identity evolve together over time. More broadly, it contributes to ongoing discussions of CLIL and bilingual education by highlighting that sustainable bilingual development is fostered not only through language instruction, but also through meaningful participation in authentic disciplinary practice.

Declarations

Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate

The study was conducted in accordance with the ethical guidelines for human research and received formal ethical approval from the National Cheng Kung University Human Research Ethics Committee (Approval No. NCKU HREC-E-110-650-2). Written informed consent was obtained from the parents or legal guardians of all participating students across all grade levels (Grades 4, 5, and 6), and assent was obtained from the students prior to data collection.

Use of Artificial Intelligence (AI) and AI-assisted technologies

During the preparation of this manuscript, the authors used the generative artificial intelligence tools (OpenAI ChatGPT and Google Gemini) solely to generate images, enhance language clarity, readability, and academic expression. All AI-assisted revisions were subsequently reviewed, verified, and edited by the authors. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Author Contribution

YHL contributed to conceptualization, methodology, curriculum design, data collection & analysis, project administration, and drafting the manuscript. SYW contributed to methodology, teacher education perspectives, and curriculum design. KKY contributed to science education expertise, curriculum design. HPC implemented the curriculum, contributed to classroom data collection and validation. All authors read and approved the final manuscript.

Availability of data and materials

The de-identified datasets generated and analyzed during the current study are not publicly available because they include data from minors and school-based records, but may be available from the corresponding author on reasonable request and subject to ethics approval and institutional permission.

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Figures

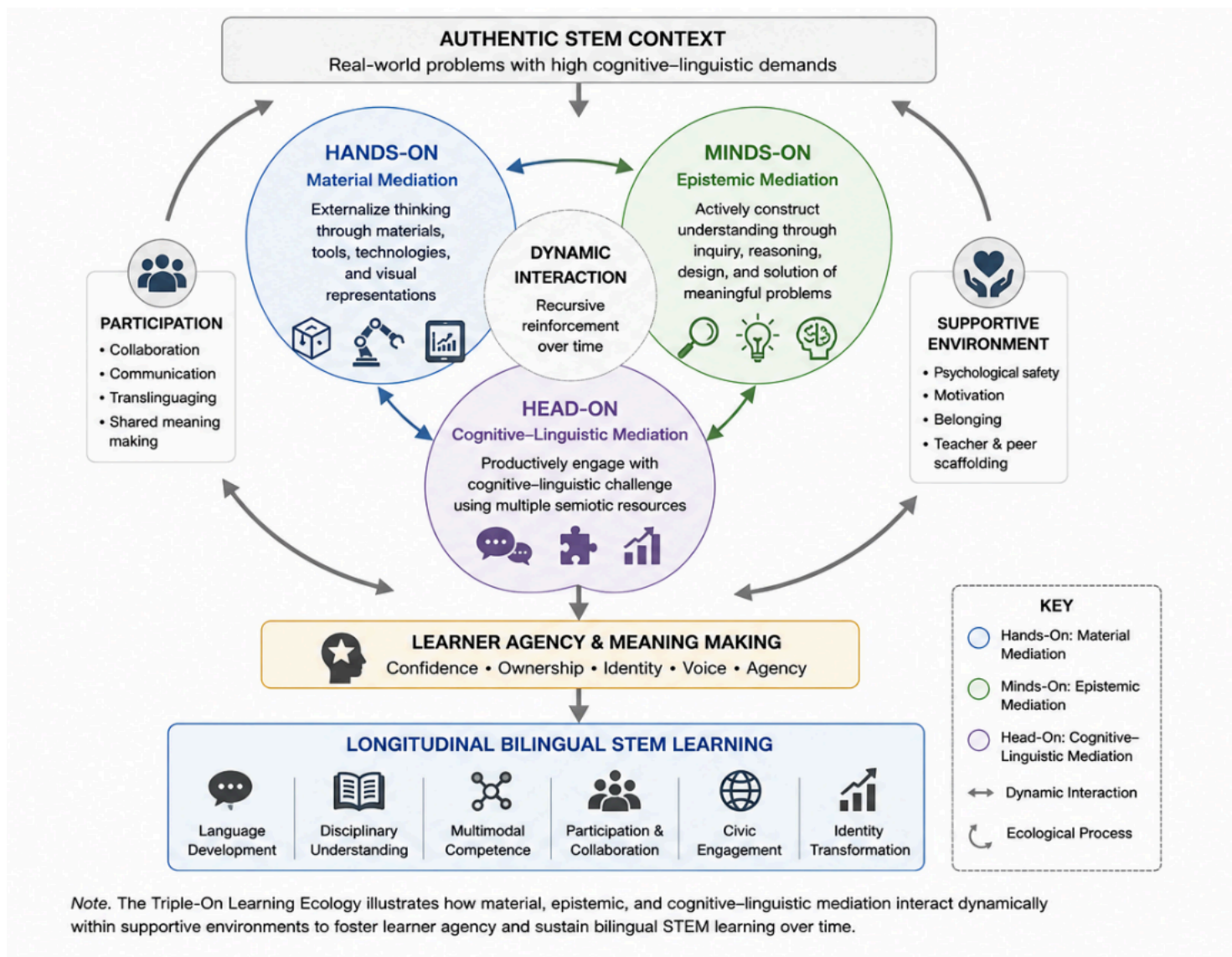


Figure 1

The Triple-On (Head-On, Minds-On & Heads-On) Learning Ecology

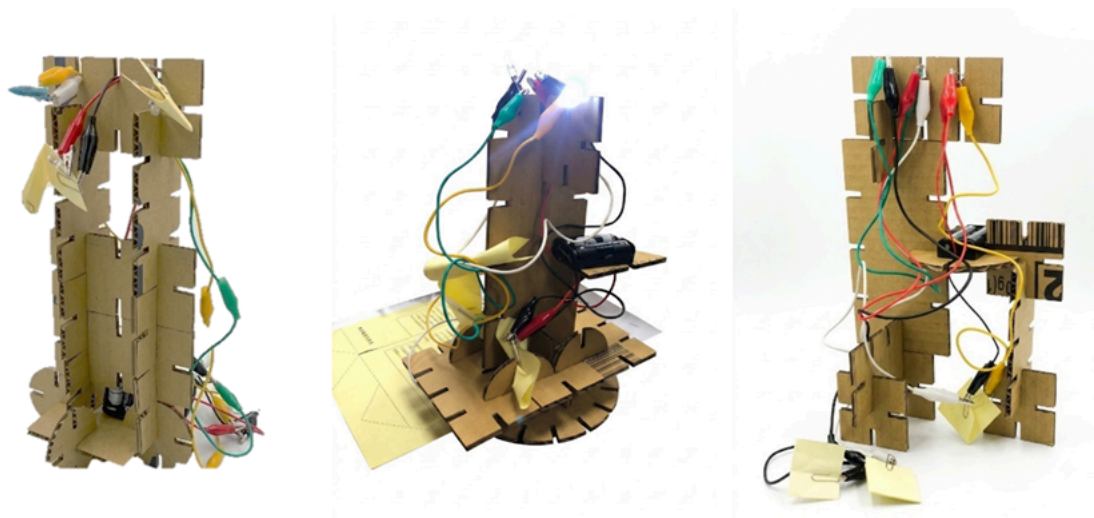


Figure 2

Recycled cardboards as the primary instructional and learning materials

Supplementary Files

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- [AppendixA.docx](#)