Bilingual Analogical Modeling and Epistemic Engagement: Exploring Elementary Students' Reasoning in Learning the Particle Model of Matter

Chiu-Wen Wang[1,2], Jing-Yi Liu[1], Chen-Yu Chen[1,3], Jing-Wen Lin[1]*

[1]Department of Science Education, National Taipei University of Education, Taiwan

[2]Yong-Shun Elementary School, Taoyuan City, Taiwan

[3]Min-An Elementary School, New Taipei City, Taiwan

jwlin@mail.ntue.edu.tw

Abstract

This study investigates how bilingual analogical modeling influences elementary students' scientific modeling practices and epistemic reasoning. Grounded in research on analogical reasoning and bilingual science discourse, we designed a curriculum that integrated multimodal scaffolds in bilingual and monolingual formats to support students' understanding of the particle model of matter (PMM). Two cohorts of sixth-grade students (N = 20) participated in a design-based implementation comparing the two instructional conditions, which highlighted the interactions among language, multimodality, and modeling. Classroom data revealed that monolingual learners flexibly used linguistic resources to construct and refine scientific models, displaying higher cognitive engagement but also revealing conceptual misconceptions. In contrast, bilingual learners experienced higher cognitive load, yet some benefited from analogical language scaffolds that enabled more sophisticated reasoning. The findings suggest that both language and analogy function as double-edged pedagogical tools. However, the purposeful integration of bilingual instruction and analogical modeling can provide chemistry teachers with practical strategies to scaffold students' reasoning about abstract and invisible scientific concepts such as PMM, thereby enhancing both conceptual understanding and classroom practice.

Keywords: Analogical Modeling, Bilingual Instruction, Particle Model of Matter (PMM), Modeling Competence, Translanguaging

1.Introduction

In recent years, science education has increasingly emphasized the role of modeling as a central epistemic practice through which students construct, test, and revise representations of scientific phenomena[1][2]. At the elementary level, however, fostering students' modeling competence remains challenging due to the abstract nature of many scientific concepts and students' developing cognitive and linguistic resources. This is especially true in the context of the Particle Model of Matter (PMM), which requires learners to reason across macroscopic experiences and microscopic explanations—an epistemic move that often exceeds the intuitive grasp of young learners [3][4]. To address these challenges, science educators have turned to analogical modeling—the process of using familiar source domains to construct models of unfamiliar scientific targets—as a promising strategy for bridging students' everyday knowledge and formal scientific understanding [5][6][1, 2]. While analogical modeling has been shown to support conceptual change and explanation generation, its implementation in classrooms is uneven, particularly when students lack guidance in mapping, evaluating, and revising their analogies in epistemically productive ways [7][8].

Although bilingual contexts may increase cognitive load and present additional challenges, when combined with analogical modeling and supported by structured analogical scaffolds, they may also create opportunities for deeper epistemic engagement. The increasing adoption of CLIL (Content and Language Integrated Learning) and translanguaging pedagogies [9][10] offers potential avenues for integrating language and content learning. Yet, their operationalization in inquiry-based science practices—especially in model-based reasoning tasks—remains under-theorized and under-documented[11]. Drawing on the DEAR modeling cycle (Development, Evaluation, Application, Revision) [6] 2.This study addresses the following research questions:

RQ1. What key modeling practices do students engage in when constructing scientific models of the PMM through analogical reasoning?

RQ2. How do students in bilingual and monolingual analogical modeling groups differ in their engagement across these modeling practices?

RQ3. In what ways do bilingual and monolingual analogical modeling scaffolds mediate students' conceptual transformation during the modeling of PMM?

2.Literature Review

2.1 Modeling as an Epistemic Practice in Science Education

Science is a process of constructing, describing, and explaining predictive conceptual models of natural phenomena [12].Within this process, models are used to organize theoretical entities and processes, explain and predict patterns in data, and are often integrated into theoretical frameworks [13]. Learning science thus requires strengthening both students' understanding of the nature of scientific knowledge and their ability to engage in scientific practices and discourse. Modeling is a core scientific practice, a fundamental means for constructing and communicating scientific knowledge, and a vital component of scientific literacy [12][14].Modeling competence essential for fostering students' abilities to understand natural phenomena, as well as to explain and predict them [6].During the modeling process, researchers have identified several steps, such as constructing, validating, applying, evaluating, and revising scientific models during modeling practice [6][12][13].

2.2 Analogical Reasoning as a Mechanism for Conceptual Change and Model Construction

Scientists often employ diverse analogies and mental simulations to generate and evaluate solutions, thereby developing theories and shifting scientific paradigms. These processes involve not only the direct application of knowledge but, more importantly, the creative reorganization and transformation of existing knowledge to discover new solutions [2][15]. Further, these results corroborate prior evidence that a structural alignment process underlies analogical comparison—even a brief analogical comparison task can confer relational insight, and a structural alignment process underlies such comparisons[15].3.When students establish object correspondences and relational correspondences between the base and target domains. Finally, they use the transferred inferences to test whether the model matches actual observations, thereby facilitating model revision [16].

Students, like scientists, can also demonstrate informal reasoning abilities in science learning, using analogical reasoning to overcome misconceptions and develop new understandings. However, elementary students often face constraints in abstraction and linguistic expression during model construction [2][18]. Young learners tend to rely on intuitive analogies, but require teacher scaffolding to advance toward structure-mapping analogies [5]1.This approach assists students in transforming everyday experiences into scientific concepts [7][17].Employing multiple analogies as scaffolds can link students' prior understanding of everyday events to knowledge in scientific domains[5]$_1$.

2.3 Language, Scaffolding, and Translanguaging in Bilingual Science Modeling

Translanguaging facilitates model construction and conceptual deepening. Students may generate and reason about models in their first language (L1) and then present and express them scientifically in the target language (e.g., English). Teachers can allow students to switch languages during group discussions to ensure depth of conceptual understanding, while progressively transitioning toward disciplinary academic language for formal presentations. Such cross-linguistic comparison not only promotes conceptual restructuring but also helps students grasp the semantic nuances of scientific vocabulary across languages—an especially critical skill for chemistry teachers who must bridge macroscopic phenome.

3.Methodology

3.1 Research Design

This study employed a qualitative design-based research (DBR) approach to explore how bilingual and monolingual analogical modeling scaffolds mediated elementary students' engagement in scientific modeling practices and conceptual transformation regarding the particle model of matter (PMM). The intervention was iteratively designed and implemented across two contrasting instructional groups—bilingual analogical modeling (BA) and monolingual analogical modeling (CA)—each composed of approximately ten sixth-grade students from comparable classrooms in a public elementary school in Taiwan.

3.2 Instructional Intervention and Scaffolding Design

The intervention was structured around three core scaffolding components:

(1) **Concept Mapping Scaffolds:** Each unit incorporated a concept map linking everyday language, macroscopic phenomena, and microscopic particle explanations. These maps activated prior knowledge and bridged everyday and scientific language.

(2) **Mover Analogy and Structural Mapping Table:** A pre-designed "mover" analogy scaffold (小精靈類比) supported students in mapping attributes of the analogy to scientific features of PMM, accompanied by a three-part structural mapping table.

(3) Four-Cycle DEAR Modeling Process: Instruction followed the DEAR cycle—Development, Evaluation, Application, and Revision [6]—guiding students to generate, test, and refine analogical models through teacher scaffolds and peer dialogue.

3.3 Data Collection

Data sources included classroom video and audio recordings, instructional materials, student worksheets, and observation notes. Classroom activities were fully transcribed to capture students' verbal and gestural modeling behaviors. Student interviews were initially planned but not conducted due to logistical constraints.

3.4 Data Analysis

A codebook-based thematic analysis [20] was used to examine transcripts, worksheets, and observation logs. Four analytical dimensions were defined:

- Analogical Strategies (R1–R4: from no analogy to self-generated microscopic analogies).

- Language Use (L1–L4: from monolingual non-academic to stable bilingual code-switching).
- Multimodal Integration (M1–M4: from single modality to integrated multimodal explanation).
- Regulatory Strategies (C1–C4: from no strategy to active modality switching).

Comparative analysis was conducted between BA and CA groups to examine how scaffolds mediated students' modeling practices and conceptual transformations (RQ2, RQ3). All transcripts, worksheets, and visual artifacts were chronologically reorganized and cross-referenced with observation notes to verify alignment with specific scaffolding elements. Analysis proceeded in three phases:

- Phase 1 – Concept Mapping: Identification of cross-linguistic term matching and semantic translation between macro and micro explanations.
- Phase 2 – Mover Analogy Tasks: Analysis of analogical strategies (R2–R4) and students' language use in mapping.
- Phase 3 – DEAR Modeling Cycle: Tracing students' engagement in Development, Evaluation, Application, or Revision to document conceptual transformation trajectories.

To ensure trustworthiness and reliability, the research team conducted trial coding, iterative refinement of categories, and maintained a complete audit trail of coding decisions and quotations.

4.Results

4.1 Students' Key Modeling Practices through Analogical Reasoning

Thematic analysis revealed three recurring practices across both bilingual and monolingual groups:

(1) **Semantic Translation and Conceptual Mapping:** Students translated PMM-related terms across languages and aligned emerging conceptual understanding with scientific vocabulary.

(2) **Analogical Construction and Model Mapping:** Students drew on everyday experiences (e.g., melting, evaporation) to construct analogies and connect observable phenomena with particle behaviors.

(3) **Linguistic Construction and Model Revision:** Students revised their models by identifying mismatches between analogical expressions and observed phenomena, using language as a reflective tool.

These findings suggest that students' analogical modeling followed a cumulative trajectory of mapping, aligning, and revising. However, deeper revision toward microscopic reasoning was not automatic and required sustained scaffolding.

4.2 Differential Engagement in Modeling Practices across Bilingual and Monolingual Groups

This section compares how students in bilingual and monolingual analogical modeling groups engaged differently in the key modeling practices identified in RQ1—(T1) Semantic Translation and Conceptual Mapping, (T2) Analogical Construction and Model Mapping, and (T3) Linguistic Construction and Model Revision. Three claims summarize the contrasting patterns of engagement.

Claim 1. Semantic Translation and Conceptual Mapping: Monolingual students interpreted; bilingual students decoded.

Monolingual students more easily understood and clearly articulated the connection between macroscopic phenomena and particle-level explanations, using their native language to refine and adjust conceptual meanings.For example, A monolingual student(TP14-CA60112) initially used the analogy of "操場變大"[the playground becoming larger"］to represent particle diffusion. When the teacher played a video on thermal expansion and contraction of gases and asked, "你的模型可以解釋這個現象嗎?"[Can your model explain this phenomenon?〕, the student responded, “No,” and revised it to, “粒子之間空隙變小，是因為冷了不想動”[The spaces between particles become smaller because they don’t want to move when it’s cold.〕The monolingual student attempted to explain the phenomenon using a model but did not deeply align it with the underlying scientific concept.

Claim 2. Analogical Construction and Model Mapping: Monolingual students invented; bilingual students aligned strategically.

Monolingual students created analogies spontaneously based on personal experiences and expressed original mappings between real-world contexts and particle behaviors. For instance, monolingual student’ analogies that compared particles to “chicken eggs” or “quail eggs” (TP09-CA60113), and “blue-shelled bird eggs” (TP09-CA60115), reflect creative and spontaneous analogical thinking. However, some analogies failed to align with core scientific concepts and lacked the potential to develop into productive scientific models.

Claim 3. Linguistic Construction and Model Revision: Monolingual students tended to remain anchored in surface-level features; Bilingual students revised their models through scaffolded alignment between language and concept.

In the modeling revision phase, bilingual students (BA) demonstrated more coherent and micro-level reasoning, particularly when supported by teacher-mediated scaffolds that guided them to align linguistic features with underlying model meanings. For example, a monolingual student (CA60115) used everyday temperature experience as a spontaneous analogy—heating a bird egg (as shown in the figure)—during the model revision stage. Although the description was fluent in language, it remained at the descriptive level, without further elaboration or coordination with particle behavior. The conceptual change stayed at the macroscopic level, making it impossible to carry out a meaningful revision of the initial model.

4.3 Modeling Scaffolds as Mediators of Conceptual Transformation

Analogical modeling scaffolds mediated conceptual transformation differently across groups. Bilingual students benefitted from structured linguistic and visual scaffolds that supported representational shifts, while monolingual students relied more on self-generated analogies, which sometimes reinforced misconceptions.

Table 1 Modeling Scaffolds & Processes as Mediators that Facilitate Conceptual Transformation

Modeling Scaffolds	**Monolingual students**	**Bilingual students**
Concept map	Step-by-step mapping– with both pre-designed and spontaneous analogies	Step-by-step mapping– with pre-designed analogies
Scaffolded reinterpretation of prior analogies (小精靈類比＝mover analogy)	Monolingual students often generate spontaneous analogies due to their linguistic familiarity, making pre-designed scaffolds less necessary—though such analogies may risk reinforcing misconceptions	Pre-designed analogies serve as scaffolding to support bilingual students in evaluating the appropriateness of models.
Four-Phase Cyclical Modeling Process (DEAR)	Model construction integrated with multimodal representations (BA60105)	Accurate language mapping and causal reasoning (CA60115)

4.3.1. Concept map

Structural mapping tables supported alignment of macroscopic phenomena with microscopic explanations. Bilingual students relied more on preset analogies, while monolingual students flexibly combined preset and spontaneous analogies.

4.3.2 Scaffolded Reinterpretation of Prior Analogies

Monolingual students often favored their own spontaneous analogies, which sometimes conflicted with scientific concepts and required strong teacher intervention. Bilingual students relied on pre-designed analogies to evaluate appropriateness, reducing the risk of misconceptions.

4.3.3 Four-Phase DEAR Modeling Cycle

The DEAR cycle promoted iterative development, evaluation, application, and revision. Peers collaborated in reasoning and model critique, while teacher scaffolds guided alignment between language and concept. Bilingual students particularly benefitted from structured prompts to reach microscopic reasoning.

5.Conclusions and Teaching Implications

This study examined how elementary students engaged in analogical modeling to learn the particle model of matter (PMM), comparing bilingual and monolingual instructional conditions. Findings across the three research questions provide insights into students’ modeling practices, the role of language, and the scaffolds mediating conceptual transformation.

5.1 Analogical modeling follows a cumulative trajectory but requires scaffolding

Students engaged in three recurring practices—semantic translation and conceptual mapping, analogical construction, and model revision. This trajectory suggests that deep conceptual transformation is not automatic but requires multi-lesson sequences with checkpoints for evaluation and revision (e.g., the DEAR cycle). One-off analogy activities are insufficient, as sustained scaffolding is necessary for students to progress from surface analogies to particle-level reasoning.

5.2 Distinct pathways for bilingual and monolingual learners

Bilingual students relied on structured supports (concept maps, word walls, mapping tables) to progressively decode and align analogy structures with particle-level concepts. Monolingual students, while fluent in generating creative analogies, often remained at the macroscopic level without explicit guidance. Teachers should adopt differentiated scaffolding:

(1) For bilingual learners: emphasize structural mapping tables, cross-language prompts, and bilingual sentence frames to lower cognitive load and foster abstraction.

(2) For monolingual learners: encourage creative invention, but follow up with guiding questions that press for causal reasoning and microscopic alignment.

5.3 Scaffolding mediates conceptual transformation differently across groups

Three scaffolds were especially influential: (1) bilingual concept maps, (2) the mover analogy structural mapping table, and (3) the DEAR cycle for sustained revision. These mediated learning in different ways: bilingual learners benefited most from translation-based scaffolds, while monolingual learners needed prompts that restructured intuitive analogies into coherent particle models. Across groups, teachers should integrate visual and multimodal supports to connect observable phenomena with the invisible particle world, a central challenge in chemistry education.

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