Science Education International
36(4)_2025,405-416
https://doi.org/10.33828/sei.v36.i4.4

International Council of Association for Science Education

REVIEW ARTICLE

Determinants of Lifelong Learning Competencies Development in the Science Classroom

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ABSTRACT

The article investigates the determinants shaping the development of lifelong learning competencies in the science classroom, proposing an instructional architecture that combines conceptual clarity, metacognitive guidance, and productive collaboration. The approach is theoretical and integrative, grounded in findings from science education research and the educational sciences, and organized into three complementary perspectives. The first perspective focuses on reflection, metacognition, and self-regulation at the moment of choosing the answer, supported by brief guiding questions with simple criteria for self-evaluation. The second perspective examines transfer as students apply their knowledge in new situations, drawing on the big ideas of science and using modeling across varied contexts. The third perspective describes the formation of scientific identity within the learning community, based on scientific dialogue, clear roles in group work, and two-way continuous feedback. These elements cultivate coherence in scientific argumentation and help build a learning community grounded in shared norms and students' voice. Conceptual findings are summarized in three tables that link psychological mechanisms to classroom practices and their intended impact, and are aligned with empirical patterns previously documented in comparable instructional settings. Teaching vignettes illustrate adaptable lesson sequences that can be easily applied in practice. The main contribution clarifies the instructional conditions that convert conceptual knowledge into adaptive, transferable learning behaviors. The implications concern lesson design and the organization of the classroom learning community by combining conceptual clarity, metacognitive guidance, and the norms of scientific dialogue.

KEY WORDS: Knowledge transfer, lifelong learning competencies, metacognition and self-regulation, science education, scientific identity

INTRODUCTION

Often a lesson begins with a short question, for example, whether a heavier bob changes the period of the pendulum. First, I ask students to predict what will happen, then to justify their answer, and finally to compare their hypothesis with what they observe and state whether the experiment validates it. When this metacognitive choice routine becomes a habit, students learn to notice their thinking at the moment of decision and to relate it to clear criteria. In this sense, the article examines how socially shared reflection supports the development of lifelong learning competencies (LLLC) in the science classroom.

This text is an invitation to dialogue among communities that meet less often than they ought to: Researchers in Science Education Research, scholars in the educational sciences, educational psychologists, theorists of education, school-based science and science teachers, doctoral supervisors, PhD candidates, and policymakers. We bring them all to the same table around a simple yet demanding question: "What exactly needs to happen during a science classroom for students to develop not only their knowledge, but also the way they learn, apply, and collectively arrive at scientifically accurate meaning?"

The framework we propose rests on three mutually reinforcing ideas. First, integrating reflection, metacognition, and self-regulation into the act of choosing an answer so that the student makes their criteria explicit and calibrates the decision. Research over recent decades shows that conceptual understanding is not transmitted but constructed in action, and its viability is seen through application in different contexts rather than repetition at the same level. We then focus on knowledge transfer, understood as the ability to apply beyond the initial context. Finally, we address the social dimension of learning, grounded in interaction, collaboration, and the formation of students' scientific identity within the learning community. These three strands do not impose a single protocol but a clear lesson architecture (the internal pedagogical structure of the physics lesson) in which students can explain why they chose a path, what led them to change their decision, and how they use the same strategy in new situations together with others.

We deliberately situate ourselves within the constructivist tradition that shifted the focus from the transmission of knowledge to the construction of meaning. We owe to Watts and Pope (1989) a formulation that has remained a touchstone for many of us: That learning science also means learning

about learning. The lesson thus becomes a workshop, not a stage. In this workshop, conceptual questions, brief moments of individual reflection, peer dialogue, self-explanation, and returning to the decision are tools that make assumptions visible and adjust the strategy. We do not aim to "tick off" methods, but to establish a rhythm of thinking that holds from one task to the next.

For the reader coming from experimental pedagogical research, the introduction prepares several central findings of the article. We will show that the metacognitive sequences of the lesson, placed at the moment of deciding how to solve the problem situation, lead to deeper and more durable conceptual understanding. We will show that reflective sequences such as "anticipate," "justify," "confront with observation," and "revise the answer," combined with pair discussions and modeling, support transfer first across near contexts and then across more distant ones. We will also show that in a learning community based on continuous feedback and scientific conversation, where the teacher acts as a coach, students' sense of belonging and scientific identity are strengthened, and performance stabilizes over time.

For practitioners, the direction is just as clear. Instead of leaving reflection as a decorative epilogue, we bring it into the heart of action. Instead of treating knowledge transfer as a hope, we make it possible through tasks with varied contexts and scheduled returns to the same central idea. Instead of seeing collaboration only as classroom organization, we use it as a space for negotiating meaning, with clear and broadly accepted criteria and roles. None of this requires additional time, but a different ordering of time. It requires that the student's decision be elicited and justified, in short that the lesson produce voice, criteria, and shared responsibility.

For policy makers in education and for doctoral supervisors, the proposal offers a design advantage. A synthesis table, which we introduce in the body of the article, links psychological mechanisms to verifiable teaching practices and to outcome indicators that can be tracked over time. The table is not a showcase summary but a working map for observation, design, and ongoing teacher development. It shows how conceptual clarity, metacognitive guidance, and the norms of scientific conversation can be aligned so that LLLC do not remain a label but become a visible consequence in students' work.

The article's structure follows the logic of three interrelated dimensions. All three are developed within the Literature Review, where the first part examines the cognitive core of the science classroom – a space where reflection and self-regulation operate close to the moment of decision, at the edge of cognitive dissonance, within the learner's zone of proximal development. The second part explores how the same cognitive mechanisms cross the boundaries of the initial context and become transferable. The third part turns to the learning community, where scientific meaning is jointly constructed and students develop their scientific identity. The conclusions and teaching implications revisit these ideas in an operational key, with cognitive and social viability as the sole criterion. We invite the reader to judge our proposal by what students can do at the end: To explain, to justify, to apply in new contexts, and to work together with the rigor of a researcher.

Grounded in this rationale, the next section reviews research that clarifies three determinants of LLLC: Reflection, transfer, and collaboration.

LITERATURE REVIEW

This section outlines the theoretical background of the study, focusing on the determinants that shape the development of LLLC in the science classroom. The reviewed literature converges around three interdependent dimensions: Metacognition and self-regulation, which enable reflective control of learning; transfer of learning, which ensures the mobility and durability of knowledge; and collaboration within the learning community, which grounds understanding in shared meaning and scientific identity. Together, these dimensions form a coherent framework for analyzing how LLLC emerge and consolidate through cognitive, applicative, and social mechanisms.

Reflection, Metacognition, and Self-Regulation

Metacognition as the core of lifelong learning competence

The development of LLLC in science classrooms starts from a core that is not visible at first sight. It is not the immediate result that captures the essence, but the way the student notices their thought, tests it, corrects it, and carries it forward into new contexts. This is the promise of metacognition and self-regulation. The recent literature is increasingly clear about their role. Metacognition no longer appears as a supporting tool, but as a condition for deep and autonomous learning. For example, the AMERT model (self-aware, self-monitor, self-evaluate, self-regulate, and self-transfer) proposed by Willison et al., offers a step-by-step ladder that is visible and assessable in the exact sciences, where moment to moment decisions have immediate consequences for the solution (Willison et al., 2023). Likewise, the meta-analysis by Zohar and Barzilai (2013) confirms the stable link between metacognition and conceptual understanding and brings reflection from the margins of a lesson to the center of its design. The useful antithesis here is the habit of leaving reflection to the end, as a decorative epilogue. Thus, far from the moment of decision, reflection often remains weakly connected to the teaching strategy and does not produce real regulation of conceptual understanding.

Constructivist foundations of reflection in science learning

The science classroom offers the right setting for this repositioning. By its investigative nature, based on formulating and testing hypotheses, on analytical reasoning, and on checking conceptual understanding, it makes visible how schemas of thought are constructed and adjusted. Constructivist

approaches that have been gaining ground since the 80s have circulated a simple and powerful idea: Meaning is not transmitted but constructed. As von Glasersfeld argues and as Mahoney maintains when he speaks about the internal restructuring of meanings through experience and self-regulation (Mahoney, 1988; von Glasersfeld, 2001), the viability of meaning is tested in functioning, not in the point-by-point mirroring of reality. Driver and Oldham (1986) add that students enter the classroom with personal conceptions of phenomena, and progress does not result from automatic replacements but from questioning and reconfiguring these ideas in tasks that require a clear justification of the steps taken. From this perspective, reflection is not a facade ornament of the lesson but a sine qua non for progress in conceptual understanding.

From process awareness to ownership of learning

The direction is set by the idea that learning science means learning about learning, which shifts the emphasis from the answer to the process and legitimizes a pedagogy in which the student examines their pathways for constructing meaning. The specialized literature describes a four-stage architecture, from observation to research activity, with an impact on self-regulation at the level of the teaching sequence (Frumos, 2008), emphasizing that metacognition rests on an order of actions that require justification and revision of strategy. In the same vein, Letina (2020), as well as Botgros and Frantzuzan (2013), place metacognition at the foundation of the learning to learn competence, that is at the foundation of LLLC, and recent works from the Republic of Moldova on taking ownership of learning and cognitive effort show that durable results appear when the student assumes conscious control of their trajectory and practices this ownership within the task itself, not only in the post lesson commentary (Silistraru and Vetrilă, 2023).

Empirical evidence for reflection integrated into the learning process

Empirical results support this view. For example, Kiviluoma et al. (2024) show that guided anticipation activates prior knowledge and improves the quality of the subsequent decision, creating the starting point for self-regulation during task execution rather than after its completion. Conceptual questions followed by discussions in pairs, within *Peer Instruction*, create the pressure to clarify assumptions and help explain the robust effects reported over time across diverse contexts (Crouch and Mazur, 2001). Likewise, post lab reflection can link the experimental approach to concept and prevent learning from being reduced to a numerical result; however, when it is placed only at the end and is not accompanied by reflection mechanisms within the lesson, it remains too far from the site of decision and does not produce an immediate regulation of strategy (Baird et al., 1991).

Experimental evidence linking self-regulation to performance

Experimental findings confirm this perspective. For example, the link between self-regulation and performance in abstract tasks is consistent. Students who monitor their errors, ask themselves questions about their steps, adjust their strategy, and consciously revisit their decisions achieve better results and more durable understanding, which brings the indicators closer to the profile of LLLC rather than the score on a single test (Banda and Nzabahimana, 2023; Dori et al., 2018). Interventions with explicit metacognitive questions increase the quality of self-explanation and the ability to apply the same strategy in new contexts. The differences between high performing students and those with average results are due more to the frequency of real time metacognitive reflection than to the amount of content reproduced (Schuster et al., 2020). The antithesis is clear. A pedagogy focused exclusively on content and speed of problem solving may produce short-term performance, but it does not activate the internal regulation mechanism that supports the development of LLLC.

Transfer and Application

If in the previous section, we saw how reflection activates the internal mechanism of learning, here we follow the natural next step: How the same strategy goes beyond its initial context and works in new ones. Knowledge transfer thus becomes a visible indicator of deep and durable conceptual understanding, not merely of a plausible answer.

Transfer as an indicator of deep understanding and scientific literacy

In the specialized literature, transfer is regarded as an indicator of deep understanding: What can be applied in new situations is more likely to be truly understood. The same idea underpins the international PISA assessments, where scientific literacy is defined as the capacity to mobilize knowledge in everyday contexts, to evaluate decisions, and to formulate data-based explanations (OECD, 2023). From this perspective, LLLC, by combining declarative, procedural, conditional, and metacognitive components, naturally overlap with scientific literacy and give it practical substance (Calalb, 2017).

Conceptual backbone and instructional conditions for transfer

For transfer to occur, instruction needs a conceptual backbone that withstands changes of context. The Big Ideas of Science model proposed by Wynne Harlen, later developed in recent literature, provides this backbone: Generative concepts that "hold" explanations together and make them extendable (Harlen, 2010). Conceptual teaching, as described by Maries et al., shifts the emphasis from collections of formulas to networks of concepts that can be rearranged when the context changes (Maries et al., 2022), in line with the idea of organizing knowledge into durable structures (Gatch, 2010; Riveros, 2020). However, the backbone alone is not sufficient. Transfer does not occur by itself. It needs explicit instructional conditions: Metacognitive scaffolding that makes the tools of thinking visible (Wiener et al., 2017), inquiry-based learning that puts concepts to work in unforeseen situations, and repeated opportunities for application across varied contexts so that the central move of problem-solving becomes stable.

Curricular and pedagogical design strategies that enable transfer

At the curriculum level, designing competencies so as to favor transfer has a tradition in science teaching. The selection of pivotal concepts, the sequencing of tasks, and the deliberate revisiting of the same relationships in different contexts have been recommended since 1986 by Driver and Oldham. In the same direction, strategies that hand over a real share of control to the learner, such as selecting essential content and planning the steps within a self-directed learning regime, show effect sizes larger than those obtained through traditional teaching (Hattie, 2023). Problem-based learning, through real-life situations, yields comparable gains, and reflective learning, when integrated into the task itself rather than left to the end, has substantial effects (Calalb and Dabija, 2024b). Interdisciplinarity, if it preserves conceptual clarity, makes cognitive structures more flexible: STEM projects can achieve notable effects, and inquiry-based science education (IBSE) remains a strong driver of transfer. By contrast, integrated curricula do not always deliver meaningful gains unless they are supported by a careful instructional architecture (Manolea, 2014).

Modeling and contextualization as drivers of transfer

A central element of this architecture is modeling. As a practice of constructing and testing mental, physical, or computational representations, modeling bridges theory and applications and provides students with a language for what remains constant and what changes when the “material” of the piece varies (Sokolowski, 2021). Contextualization is just as important. Lessons anchored in real life situations increase scientific literacy and motivation, and well guided integrative teaching supports the flexibility required for transfer.

Cognitive conditions and feedback mechanisms that stabilize transfer

The literature also points to the specific conditions, the levers that regulate transfer. The task should be positioned at the edge of the zone of proximal development, challenging enough to require a rearrangement of schemas but not so difficult that it breaks the thread of understanding. Sustained cognitive effort, accompanied by explicit goals owned by the student, stabilizes transfer (Calalb, 2020). Conceptual depth is an essential predictor: Rich internal representations support transfer to new contexts (Saba et al., 2023). Calibrated feedback, especially following peer discussions, accelerates transfer because it links the decision directly to visible and shared criteria, in the logic of visible learning and diagnostic guidance (Domilescu and Iorga, 2024). Assessment is not merely a measuring tool either. The cognitive processes activated during testing consolidate and extend learning, contradicting the idea that learning occurs exclusively during direct instruction (Polack and Miller, 2022).

The teacher’s scaffolding role in supporting transfer

Within this framework, the teacher’s role is decisive. Successful transfer is built on scaffolding that combines instructional, conceptual, and metacognitive support: Clarity about the steps, the relationships, and one’s own strategy (Ding et al., 2011). Thus, the teacher provides two-way feedback that guides the next step and values any student attempt, avoiding categorical and premature verdicts.

Constructivist balance between conceptual clarity and application

In this way, transfer is not an isolated performance but a balance between conceptual clarity and openness to application: Well-grounded concepts mobilized creatively in new, authentic, and challenging contexts (Bravo González and Reiss, 2021). Constructivist strategies that combine inquiry, guided reflection, and collaboration create this balance and directly support the development of LLLC. The science classroom becomes a workshop where students learn to recognize the tools of thinking and carry them from one context to another.

Thus, transfer is consolidated not only through the learner’s inner dialogue but, above all, within the learning community, through the negotiation of meaning, shared norms of scientific conversation, and the teacher’s role as a learning coach who calibrates requirements, checks conceptual tolerances, and connects individual progress to the standards of the group. In this way, the next section explores how this social dynamic amplifies transfer and defines the criteria that make an idea viable for everyone, not just for one student.

Interaction, Collaboration, and Scientific Identity

Once the mechanisms of transfer have been outlined, attention shifts to the environment where they take root: The learning community. Here ideas are not confirmed in solitude but are tested and calibrated in dialogue; it is also here that an equally important stake for LLLC comes into view: Scientific identity, understood as a sense of belonging to the discipline and the legitimacy of one’s own voice in the classroom’s scientific conversation.

Dialogue and shared meaning in the learning community

Recent research supports shifting the focus from teacher centered instruction to practices focused on students’ explanations and the joint construction of meaning. Lessons that make productive use of dialogue render students’ assumptions preconceptions visible, set explicit criteria for argumentation, and strengthen understanding (Dodlek et al., 2024). Team structures with peer leadership increase cooperation and shared responsibility (Morris et al., 2021). Recent curricular guidelines point in the same direction, promoting an educational model based on interaction, cooperation, and meaning making in learning communities through collaborative activities and integrated STEM or STEAM projects (MECC, 2020). The contrast remains useful. A teacher centered, lecture-based approach, in which the teacher delivers content and controls the pace and validation, may provide answers but does not cultivate scientific identity.

Interactional model and shared regulation

The theoretical foundation of this shift has two components. On the one hand, the interactional model supports curriculum

design around the social negotiation of meaning and group activities. On the other hand, the Self-Regulated Learning; Co-Regulated Learning; Socially Shared Regulation of Learning perspective describes how individual self-regulation interweaves with co-regulation and socially shared regulation in collaborative tasks, underpinning strategies centered on active and exploratory learning (Hadwin et al., 2018). From this point of view, reflection, and regulation become public processes: They are practiced together, and the criteria are set jointly.

From shared regulation to the formation of scientific identity

In the classroom, this perspective translates into practice. The teacher works as a coach or as the learning site supervisor: He or she does not dictate the steps, but calibrates the requirements, asks for clear conceptual tolerances, checks alignment with the conceptual "plan," and lets the team solve. Group work, projects, scientific inquiry, and debate put students in a position to think out loud, negotiate explanations, and assume responsibility for a joint decision. These are the very conditions under which scientific identity of students is formed (Pols et al., 2021). Thus, the lesson becomes a place where students negotiate meanings and develop their voice within a community.

Collaborative practices that cultivate scientific thinking and identity

Thus, the practices that keep the team in the productive tension of truth seeking are not exotic, but they do require rigor. Guided laboratory work grounded in authentic inquiry deepens conceptual understanding and gives students the experience of doing research, strengthening their scientific identity (La Braca and Kalman, 2021). Socratic dialogue, led by questions that demand criteria and evidence, helps reconstruct concepts (DePierro and Garafalo, 2003). Furthermore, peer instruction sequences, when used as a framework for deliberation rather than a mechanical ritual, familiarize students with the norms of scientific reasoning: Claim, justification, and revision. Across these settings, collaboration is not merely a way to organize the class but the vehicle through which students learn to think and communicate scientifically.

Participation, recognition, and feedback in building scientific identity

Identity is not reducible to declarative knowledge. It grows through participation and recognition: Being invited into conversation, having one's explanation heard, receiving meaningful feedback, and claiming a role in collaborative problem-solving. Studies published in Physical Review Science Education Research show that belonging and recognition from teachers and peers strengthen science identity and support long-term learning (Cwik and Singh, 2021). A classroom climate that normalizes not-knowing and invites metacognitive dialogue gives students voice and space for informed participation. Feedback makes the difference: Its impact is substantial when it is clear, timely, and personalized, when the student knows what to do with it tomorrow; otherwise, the message is rejected or ignored. Peer assessment, designed with shared criteria and applied across successive tasks, transforms evaluation from a punitive end point into an integral part of learning, with effects on reflection, performance, and group cohesion (Sluijsmans et al., 2002).

The learning community as the space of social viability

Viewed through the lens of transfer, the community adds what isolated situations cannot produce: Social viability. An explanation does not become "ours" until it has passed a public test and can be defended, by the same criteria, by several members of the team. This is not just an intuition. For demonstrable tasks, small groups often outperform the best individual member (Clément et al., 2013; Laughlin et al., 2003, 2006). This is the difference between a one-off success and a competence that endures. In terms of LLLC, communication, collaboration, socially shared regulation of learning, and feedback become the infrastructure of participation and belonging, while the teacher, in the role of coach, provides the setting in which the community's standards are clarified and practiced.

METHODOLOGY

Type of Study

This article is a conceptual and integrative study situated at the intersection of science education research, cognitive psychology, and the educational sciences. Its purpose is to synthesize findings from recent research and to outline a coherent theoretical framework focused on the development of LLLC in the science classroom. The analysis examines how reflection, transfer, and collaboration operate as interconnected determinants of LLLC, linking psychological mechanisms such as metacognition, self-regulation, and socially shared regulation of learning with teaching practices that can be observed, modeled, and adapted in the classroom.

The methodology is interpretive and explanatory. It identifies recurrent patterns across studies, integrates them into three complementary dimensions of reflection, transfer, and collaboration, and illustrates their classroom relevance through vignettes inspired by authentic teaching situations. Rather than testing hypotheses statistically, the study seeks theoretical coherence and pedagogical viability, evaluated through the clarity, transferability, and applicability of the proposed framework.

Conceptual Sources and Selection Criteria

The study draws on a corpus of international and national research in science education, cognitive psychology, and educational sciences. International sources were selected from Scopus and Web of Science journals such as *Science Education, Science Education International, and Physical Review Science Education Research*, while regional studies published between 2012 and 2024 provided contextual insights into competence-based instruction in Moldova.

Sources were included for their conceptual relevance to LLLC, theoretical consistency, and grounding in empirical or analytical evidence. The selected literature addresses reflection and self-regulation, transfer and application of knowledge, and collaboration within learning communities. Some studies are cited across multiple subsections, as their findings connect several dimensions of LLLC. This interrelation of perspectives allowed the identification of recurring conceptual relationships and supported the construction of an integrative framework that reflects both cognitive and social mechanisms of lifelong learning.

Analytical Procedure

The analysis followed a qualitative and interpretive procedure aimed at connecting and refining the conceptual mechanisms that explain the formation of LLLC in science education. Sources were examined comparatively to trace relationships among ideas concerning reflection, transfer, and collaboration. Through iterative reading and cross-referencing, these relationships were consolidated into a coherent framework linking cognitive, applicative, and social processes. Particular attention was given to instructional models that scaffold students' inquiry and metacognitive engagement in science learning, following recent recommendations for structuring inquiry as a guided yet autonomous process (Petersen, 2022). The analytical focus was on ensuring theoretical consistency and the practical relevance of the concepts for classroom implementation.

Illustrative Vignettes

Vignette 1. Decision and reflection routine

The lesson opens with a moment of reflection. The teacher presents a simple pendulum and asks whether a different mass of the bob will change the period. Each student briefly writes an answer and a justification. One student writes that a heavier bob will swing faster and feels confident in his answer. The teacher does not contradict him but invites him to name the reasoning behind his decision and reminds the class that mistakes reveal how a thought was formed without sufficient deliberation. A short dialogue with his desk mate follows. Together they look for what remains invariant across situations, then return to the initial decision and explain briefly whether they keep or change their answer. In the second part of the lesson, the class runs a short experiment with two bobs of different masses but identical string length and amplitude. Observation is treated not as a verdict but as a mirror for reasoning. Students compare what they predicted with what they observed, note what led to changing or keeping their hypothesis, and name the steps they will use when the context changes. The teacher does not give a verdict but asks for criteria. At the end, the class formulates two self-check questions that will open the next lesson. Without reliance on a fixed protocol, the lesson weaves a rhythm in which hypotheses become visible, decisions are justified, and strategies gain the power to move from one context to another.

Vignette 2. Apprenticeship in conceptual transfer

The class solves the "sled on ice" problem. Free-body diagrams are correct, and the conclusion is clear. Then the teacher changes the context: The same situation on asphalt, with a skateboard. New formulas and hesitations appear. Students return to their tools: They identify forces, separate what remains constant from what changes, and preserve the central procedure of the solution, projection on axes and force balance. The parallel problem is solved correctly although the material context differs. What remains is craftsmanship: Essential relations are recognized, and the sequence of steps fits without new recipes. This is the image of transfer we seek.

Vignette 3. Team feedback and shared decision

Teams compare two solutions proposed by classmates using a short worksheet: What hypothesis was used, what data support it, what step of the strategy is kept, and what step changes. The teacher asks for evidence for every claim and clarifies acceptable conceptual tolerances. Each team formulates a joint decision and a follow-up check step for the next task. Transfer thus becomes a collective outcome rather than an individual result.

We have to underline that the three teaching vignettes illustrate mechanisms through which students expand their learning horizons and integrate more fully into scientific activity. Their impact is supported by empirical patterns previously documented in comparable instructional settings.

Vignette 1. The prediction–justification–revision structure enables students to monitor their thinking and recalibrate explanations. Prior results show measurable improvements in metacognitive functioning, with mean scores on a five-point Likert scale increasing from 3.262 to 3.615 for girls (Wilcoxon $z = 2.920$, $p = 0.002$, Effect size (ES) = 0.328). Such patterns indicate that students become more capable of evaluating the soundness of their reasoning and adjusting their strategies, a fundamental capacity for lifelong learning (Calalb and Dabija, 2024a).

Vignette 2. Using overarching ideas as anchors supports the generalization of reasoning across item types. In the electrokinetics study, students working within a conceptually structured sequence demonstrated more stable performance across conceptual and conditional items. On a ten-point scale, the experimental group obtained higher mean scores (7.37 vs. 5.98; $d = 0.54$), and reduced variability (standard deviation = 2.23 vs. 2.41) reflected more consistent use of underlying principles. This pattern aligns directly with the vignette's mechanism: Broadening conceptual horizons by helping students reorganize new ideas around transferable scientific structures (Dabija, 2025).

Vignette 3. Structured peer discussion exposes students to disciplinary norms of explanation and reasoning. Empirically, this was reflected in improved distributional profiles of explanation quality, with the post-instruction skewness shifting from mildly positive to –0.585, indicating a higher concentration of well-formed, coherent scientific responses.

Students' performance on explanatory items was both higher in mean level and more consistent, demonstrating how collaborative dialogue fosters integration into scientific discourse practices.

Empirical indicators for metacognition, conceptual transfer, and scientific dialogue are provided in Table 1.

FINDINGS

Cognitive Foundations of Reflective Lesson Design

Our findings confirm that the formation of LLLC begins in the inner architecture of the lesson, where reflection and self-regulation are deliberately integrated into the act of deciding. The science classroom becomes a space not for reproducing solutions but for observing one's own reasoning. The teacher's role shifts accordingly from a sole source of validation to a partner in reflection and exploration, a finding consistent with recent research identifying distinct teacher profiles associated with inquiry-oriented and metacognitive lesson structures that promote reflective and self-regulated learning (Greitāns and Namsone, 2024). Support is provided through Socratic dialogue, formative self-assessment, and metacognitive rubrics that invite students to formulate criteria, justify choices, and connect their steps to principles (Skorbakk and Gamlem, 2025; Udoh, 2012). Reflection thus ceases to be a decorative epilogue and becomes a real mechanism of learning.

The balance between support and autonomy appears as a decisive factor. When guidance is excessive, self-regulation loses meaning; when scaffolding alternates with real decision-making, learning gains coherence and persistence. Effective interventions respect the rhythm of understanding, alternating phases of modeling and independence, while taking cognitive load into account (Hartelt and Martens, 2024). In this dynamic, metacognition grows not from explanations but from genuine dilemmas – those moments when students have to choose, to test, and to correct themselves.

Metacognition operates as both awareness and control. It is the inner dialogue in which the student evaluates the quality of reasoning, detects uncertainty, and plans the next step. In authentic situations, where the problem cannot be solved by recall alone, students learn to pause, ask "what led me to this choice?", and revise the path in light of evidence. Gradually, the classroom becomes a workshop for reasoning, where error is not failure but information about the process. In such lessons, reflection, self-monitoring, and self-regulation converge into a single routine of learning that follows a simple rhythm: Anticipate, justify, check, and revise. Thus, through this process, understanding becomes durable and transferable.

Knowledge Transfer and Cognitive Viability across Varied Contexts

Findings show that knowledge transfer does not occur by repetition, but by reorganization. Understanding becomes transferable when students can detach a principle from its initial situation and reapply it to a new one without losing coherence. In this sense, transfer represents the proof of deep learning: The ability to preserve the essential relations while adapting to new conditions. A coherent instructional architecture supports this process, where reflection, feedback, and conceptual clarity work together (Hajian, 2019). This perspective aligns with the definition of scientific literacy adopted in the PISA 2022 framework, which views understanding as the ability to mobilize knowledge in authentic, data-based reasoning, and problem-solving. In classroom practice, this means designing tasks that require the flexible application of concepts across contexts. Lessons that deliberately vary a single element of a familiar situation, such as the mass of the object, the angle of inclination, or the medium in which motion occurs, make the limits of the concept visible and invite students to articulate what remains constant and what changes. This small but decisive step transforms explanation into reasoning.

Transfer depends on aligning scientific content with transversal competencies such as planning effort, estimating task difficulty, and adjusting strategy in real time (Ardelean et al., 2012). Progress becomes visible not through formal repetition but through the quality of the decision. When students are required to compare their initial answer with observation, justify whether they keep or change it, and identify the criterion that guided the change, they practice cognitive control in its most concrete form. Studies confirm that such explicit comparison enhances both self-regulation and conceptual understanding (Lebedev et al., 2020).

Table 1: Empirical indicators for metacognition, conceptual transfer, and scientific dialogue

Vignette	Mechanism	Empirical indicator	Experimental data
1. Reflective metacognition	Monitoring and adjustment of reasoning	Improvement in metacognitive functioning	• Girls: 3.262→3.615 • Boys: 3.182→3.278 • Wilcoxon z=2.920, *P*=0.002, • ES=0.328
2. Conceptual transfer	Cross-context conceptual stability	More consistent use of principles across item types	• Experimental: M=7.37, SD=2.23 • Control: M=5.98, SD=2.14; • Cohen's d=0.54
3. Collaborative scientific dialogue	Integration into scientific discourse	Higher coherence and concentration of well-formed explanations	Post-instruction skewness=–0.585, indicating clustering of coherent responses

M: Mean, SD: Standard deviation, ES: Effect size

Other evidence supports the same direction. Peer leadership programs and structured collaboration strengthen autonomy, persistence, and reflective engagement, while the explicit teaching of metacognitive routines helps students maintain control over their reasoning across diverse situations (Cwik and Singh, 2021). At a deeper level, the notion of *intellectual humility* – the willingness to recognize one's limits and adjust strategy – anchors the ethical dimension of transfer (Sundstrom and Cardetti, 2021).

Taken together, these results converge toward the idea of *cognitive viability*: A concept or strategy is viable when it continues to function beyond the context in which it was learned. The capacity to justify, modify, and reapply knowledge without external prompts marks the transition from understanding to lifelong learning. In this perspective, transfer is not an accident of practice but the signature of a mind that learns deliberately, aware of its own reasoning.

The Learning Community and Scientific Identity

Findings emphasize that the durability of learning depends on its social anchoring. Knowledge becomes stable when ideas circulate within a community that recognizes, questions, and refines them. In such a setting, the teacher is less an evaluator than a coach who helps students negotiate meaning, calibrate conceptual tolerances, and connect personal reasoning to shared norms of understanding. The focus shifts from producing answers to building explanations that can withstand collective scrutiny. Reflection, once private, turns into a joint act of reasoning in which arguments are tested, refined, and re-framed through dialogue.

Peer assessment and structured conversation guided by explicit criteria provide the framework for this shared reflection. Recent evidence also shows that cooperative learning structures strengthen peer relationships, academic support, and overall engagement within science classes (Kebede et al., 2024). Each argument must be supported by evidence, and the group's validation functions as a mirror for conceptual clarity. This collective calibration transforms error into common ground for improvement rather than a mark of failure. Supportive interactions with teachers and peers foster students' scientific identity and deepen their long-term commitment to science education. The sense of being heard and contributing meaningfully reinforces both self-efficacy and intellectual integrity.

The classroom thus evolves into a miniature scientific community – one that values transparency of reasoning, respect for evidence, and mutual recognition. Within such a culture, collaboration and cognition are no longer separate processes but two faces of the same practice: Understanding sustained by communication.

Empirical Evidence Supporting the Three Learning Dimensions

Although the present article is conceptual, empirical evidence from our previously published studies conducted in comparable instructional settings provides a clear picture of the types of student changes typically observed when prediction–justification cycles, reflective self-evaluation, and peer-guided scientific dialogue are implemented.

First, students' scientific identities showed measurable strengthening across several cohorts. Longitudinal data indicated a progressive normalization of performance between boys and girls, with physics perceived as more accessible and less gender-coded. Achievement gains across school years (for example, laboratory performance increasing by 9.4% from Grade 6 to Grade 8 and summative performance increasing by 8.0%) reflect a more stable sense of belonging and competence within scientific learning environments (Calalb and Zelenschi, 2024).

Second, self-assessment capabilities improved clearly, particularly in metacognitive monitoring and confidence calibration. In a study with 110 seventh-grade students, metacognition increased by 3.0% in boys and 10.8% in girls (Wilcoxon z = 2.920, p = 0.002, ES = 0.328). Attitude scores increased modestly (3.5–3.9%), indicating a more accurate self-positioning and greater readiness to engage in reflective judgment (Calalb and Dabija, 2024 a).

Table 2: Empirical indicators for scientific identity, self-assessment, and scientific speaking

Dimension	Indicators and findings	Quantitative data
Scientific identity	• Greater accessibility of physics • Reduction of gender-based differences • Improved sense of belonging • Progressive achievement growth across school years.	• Increase in lab performance with 9.4% from 6th to 8th grade • Increase in evaluation results with 8.0% from 6th to 8th grade • Gender gap nearly eliminated by 10th grade 10, physics perceived as "less masculine"
Self-assessment capabilities	• Improved metacognitive monitoring • Clearer self-evaluation • Higher alignment between perceived and actual performance • Slight increase in attitudes.	• Metacognition gains: Boys+3.0%, girls+10.8% • Wilcoxon: z=2.920, *P*=0.002, ES=0.328 • Attitude increase: +3.5–3.9%
Scientific speaking skills	• More coherent explanations • Greater use of scientific language • Stronger justification structures • Improved conditional reasoning.	• Post-test: Experimental M=7.37, control M=5.98 • Effect size: d=0.54 • Distribution skewness: –0.585 (concentration of high-quality reasoning)

M: Mean, ES: Effect size

Table 3: Synthetic framework for developing LLLC in the science classroom

Cluster	Premise	Paradigm	Practices	Impact
1. Metacognition	Metacognition and self-regulation	Active reflection at the point of decision	Prediction and revision; brief write ups; pair discussion; compare with observation	Autonomy
2. Transfer	Transfer as proof of understanding	Concept centered teaching and modeling	Identify invariants; modeling; isomorphic problems across contexts	Adaptive transfer
3. Interaction	Social identity	Students' voice and scientific conversation	Criteria guided dialogue; roles; Peer Instruction; bidirectional feedback	Scientific identity

LLLC: Lifelong learning competencies

Third, scientific speaking skills improved substantially under the combined use of conceptual questions and peer explanations. In electrokinetics unit, students in the experimental group outperformed those in the control group (post-test M = 7.37 vs. 5.98, d = 0.54), with a strong negative skew in score distribution, signaling a higher concentration of fully articulated, evidence-based explanations. These outcomes consistently show that structured peer dialogue and conceptual reasoning cycles foster clearer, more coherent scientific discourse (Dabija, 2025).

A consolidated summary of these empirically observed changes is provided in the Table 2.

CONCLUSIONS AND DIDACTICAL IMPLICATIONS

This study followed a single conceptual thread through three convergent perspectives: Metacognition, transfer, and social regulation of meaning, as scientific identity takes shape. Together, these perspectives point to the need for a flexible instructional architecture that brings together conceptual clarity, metacognitive guidance, and coherent norms of scientific conversation in the classroom, such as clarity of hypotheses, evidence-based argumentation, and joint validation of results. We next set out conclusions and operational implications using a single validation criterion: Cognitive and social viability, measured by students' ability to explain why they choose a path, what led them to change it, and how they apply the same strategy together in new contexts.

Thus, Table 3 synthesizes the core ideas for developing LLLC in the science classroom. The "Premise" column states the starting idea for each cluster: For metacognition, that self-regulation and reflection are conditions of deep learning; for transfer, that conceptual understanding is tested through application in new contexts; and for interaction, that a student's scientific identity has a social component tied to participation and recognition.

The "Paradigm" column captures the shift of emphasis in choosing instructional strategies: For metacognition, reflection becomes active and is situated at the point of decision, the teacher facilitates, and the student self-regulates their learning; for transfer, instruction is concept centered and problem-solving is guided by the metacognitive routine; and for interaction, the classroom scientific conversation places students' voices at the center and distributes responsibilities.

The "Practices" column specifies, for each cluster, an operational anchor that is explicit and easy to implement. "Prediction and revision" names the metacognitive choice routine (anticipate, justify, check against observation, and revise) enacted at the point of decision, typically through a minute of writing, a brief peer exchange, and comparing the hypothesis with the data. "Modeling" designates the construction and testing of representations (force diagrams, axis projections, graphs, equations, and simulations), with a clear separation between quantities that remain constant and elements that vary with context, so the same schema can be carried over to sister problems. "Scientific conversation" means dialogue guided by agreed criteria (clarity of the hypothesis, link to the data, and justification of the strategy), with explicit roles (speaker, listener, and rapporteur), possible peer instruction integration, and two-way feedback; the decision is formulated jointly and tied to a check for next time.

Finally, the "Impact" column brings together both assessment cues and expected results. "Autonomy" means motivated decisions in real-time and owned strategies; indicators: The student justifies the choice, explains what was revised, and plans the next step. "Adaptive transfer" means the same functional schema operating in new contexts; indicators: Correct applications in other contexts, preservation of the central move in problem-solving, and reference to criteria. "Scientific identity" means belonging and a legitimate voice in the class scientific conversation; indicators: Consistent participation, taking on roles, and adherence to shared norms.

With this framework in mind, we move from framework to practice and clarify how reflection, metacognition, self-regulation, transfer, collaboration, and scientific identity are enacted in the classroom.

Reflection in science is most effective when it is integrated into the very act of deciding. The concept of reflection-in-action names the moment when the student catches an assumption and tests it on the spot, not retrospectively (Dewey, 1933; Schön, 1992). A brief, data-anchored self-explanation fixes the link between step and principle, and the self-explanation effect supports conceptual consolidation (Chi et al., 1994; Moon, 1999). In practice, two recurring questions: "What led me to choose?" and "what evidence would change my choice?"

turn error into a navigational signal and keep reflection close to the decision point.

Implication for teaching: Build short "predict, check, and explain" minutes right before key decisions, and post the two anchor-questions on the board.

Metacognition combines monitoring and control: The student evaluates the degree of their understanding and deliberately adjusts their strategy. In our framework, metacognition appears as a premise for deep conceptual understanding and autonomous learning. In practice, judgments about one's own learning are often imprecise; when calibrated through short cycles of prediction, checking against observation, and self-explanation, they become instruments of regulation (Knight et al., 2022; Wang et al., 2021). These routines fit within the perspective of self-regulated and collaborative learning, where individual regulation interweaves with co-regulation and socially shared regulation, provided that support alternates with genuine steps toward autonomy and takes the task's cognitive load into account.

Implication for teaching: Require that each decision be "named" the chosen strategy plus the reason in one-two lines, then explicitly compared with observation.

Self-regulation operates as a cycle: Planning with goals and criteria, monitoring in action, reflecting on the result, and adjusting for the next iteration. Committed goals and clear criteria support cognitive effort and strategic decisions. Ongoing assessment, anchored in criteria and concrete steps, sustains the regulation cycle, and peer assessment anchors it socially (Molin et al., 2021). Operationally, the lesson gains clarity through an initial micro planning, a midpoint check, and a final commitment to the "next step," preparing transfer to similar tasks (Calalb and Dabija, 2024).

Implication for teaching: Open the lesson with "what I aim to achieve today" criterion plus step, pause midway for a 60 second checkpoint, and close with each student noting their "next step."

Transfer becomes stable when instruction rests on generative concepts and modeling, so explanations can be rearranged as the context changes. The lesson starts from the idea that "holds" and returns to it in varied situations, deliberately changing one element to make the features of the new context visible. Tasks sit at the edge of the zone of proximal development, with goals owned by the student and sustained cognitive effort; conceptual depth is checked through feedback, and the testing functions as learning (Hattie, 2023). In practice, minicycles of design, prediction, trial, and revision, repeated on isomorphic problems, consolidate the strategy for transfer (Ivanjek et al., 2016).

Implication for teaching: Construct pairs of isomorphic problems by varying a single element, and explicitly require a "what stays constant/what changes" list before solving.

The learning community makes meaning a public good. When arguments are formulated together and used in brief discussions, explanations become testable and replicable. The interactional model, together with the perspective of self-regulated, co-regulated, and socially shared regulation of learning, shows that strategy is strengthened through shared tasks. In practice, the teacher works as a coach, sets conversation norms, assigns roles, and requires data-based arguments, while peer assessment becomes part of learning and increases cohesion and transfer.

Implication for teaching: Post the norms and roles, run short rounds of "state the hypothesis/show the data/revise," and have the rapporteur publicly note what stays and what changes.

Scientific identity is formed through authentic participation and recognition, when the student's voice is heard and evaluated against criteria that are clear to all. Studies show that a sense of belonging to the learning community, supported by teachers and peers, promotes persistence and long-term learning in science. Team-based laboratories with teacher guidance and research projects provide authentic practice that strengthens scientific identity. A climate that normalizes not knowing and cultivates intellectual humility opens space for adjusting strategy and for shared responsibility.

Implication for teaching: Rotate roles across activities, require students to present their decision (why and on what evidence), provide brief opportunities for publicly presenting their steps, and explicitly acknowledge contributions to the joint solution.

In this way, the development of LLLC in science education becomes not only a cognitive achievement but also a social and ethical commitment shared within the learning community.

ACKNOWLEDGMENTS

This work was carried out within the FIZLAB 2.0 project, supported by Grant 040103 awarded by the Ministry of Education and Research of the Republic of Moldova.

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