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MEELI RANNASTU-AVALOS

Designing asymmetric digital collaboration for inquiry science learning

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Designing asymmetric digital collaboration for inquiry science learning

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Institute of Education, Faculty of Social Sciences, University of Tartu, Estonia

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This doctoral study is based on the following publications, which are referenced in the text by their Roman numerals.

Article I

Rannastu, M., Siiman, L. A., Mäeots, M., Pedaste, M., & Leijen, Ä. (2019). Does group size affect students' inquiry and collaboration in using computer-based asymmetric collaborative simulations? In *Advances in Web-Based Learning–ICWL 2019: 18th International Conference, Magdeburg, Germany, September 23–25, 2019, Proceedings 18* (pp. 143–154). Springer International Publishing, https://doi.org/10.1007/978-3-030-35758-0_38

Article II

Rannastu-Avalos, M., Mäeots, M., & Siiman, L. A. (2023). Koostöise probleemilahendamisoskuse kujundamine uurimuslikku õpet kasutades. *Estonian Journal of Education/Eesti Haridusteaduste Ajakiri*, *11*(2), https://doi.org/10.12697/eha.2023.11.2.08

Article III

Rannastu-Avalos, M., Siiman, L., & Mäeots, M. (2025). Understanding collaborative problem-solving with smartphone-based asymmetric simulations in an authentic inquiry science lesson. *Journal of Baltic Science Education*, *24*(4), https://doi.org/10.33225/jbse/25.24.684

The author contributed to the publications in the following way:

Article I: Participated in the creation of the study design, participated in the formulation of the research questions, planned and carried out the data analysis, and contributed to the paper as the second author.

Article II: Developed the research design, adapted and developed data collection tools, led the data collection and analysis, drafted the manuscript, and completed revisions following peer review. Served as lead author in collaboration with co-authors.

Article III: Formulated the research questions, designed the study and instruments, managed data collection and analysis, wrote the original manuscript, and incorporated reviewer suggestions in revisions. Served as lead author in collaboration with co-authors.

LIST OF ABBREVIATIONS

ATC21S	–	Assessment and Teaching of 21st Century Skills. An international research framework emphasizing collaborative problem-solving and related 21st-century competencies.
CLT	–	Cognitive Load Theory, a principle guiding interface design to manage intrinsic and extraneous processing demands, eliminate split-attention effects, and free working memory for scientific reasoning.
CPS	–	Collaborative Problem Solving, the process through which two or more individuals coordinate cognitive and social processes to jointly solve a problem.
CSCL	–	Computer-Supported Collaborative Learning, a theoretical and practical framework for understanding and designing technology-mediated collaborative learning.
CVS	–	Control of Variables Strategy, an inquiry reasoning strategy used to design fair tests by systematically manipulating independent variables while controlling others.
DBR	–	Design-Based Research, a methodology emphasizing iterative design, implementation, and refinement in real-world educational settings.
F-F	–	Face-to-Face, specifying in-person collaboration where students work together orally and visually without screen sharing.
IBL	–	Inquiry-Based Learning, a pedagogical approach that engages students in investigating scientific questions through exploration, experimentation, and reflection.
K1, K2, K3	–	Knowledge Dimensions, different levels of content understanding and inquiry knowledge measured in the studies: K1 (subject knowledge recall), K2 (conceptual understanding), K3 (inquiry knowledge and applied reasoning).
KPLO	–	Koostöine probleemilahendamisoskus (Estonian), Collaborative Problem-Solving Skills, particularly as conceptualized in Estonian educational contexts.
RRL	–	Remember-Recall-Learning, a three-indicator coding protocol used to assess metacognitive development by tracking accurate recall, self-judgment of correctness, and evidence of conceptual growth.
SRL	–	Self-Regulated Learning, goal-directed metacognitive activity in which learners plan, monitor, and adjust their own thinking and strategies.
SSRL	–	Socially Shared Regulation of Learning, the extension of SRL to small-group contexts, where peers co-construct goals, monitor progress, negotiate plans, and evaluate outcomes together.
RQ	–	Research Question.

TEAC – Technology-Enhanced Asymmetric Collaboration, the theoretical and practical framework developed in this thesis to support role-based, digitally scaffolded collaboration in science learning.

UT – Uurimuslikud teadmised (Estonian), Inquiry Knowledge (identifying and relating variables)

1. INTRODUCTION

1.1. Background and Context

Contemporary societal challenges increasingly require individuals to engage with complex problems that cannot be resolved through disciplinary knowledge alone. As argued by Andrews-Todd et al. (2023) and Burns et al. (2024), issues such as technological change, environmental sustainability, and public health demand coordinated reasoning, shared sense-making, and adaptive self-regulation. Within this context, science education is expected to cultivate not only conceptual understanding but also collaborative inquiry, disciplined reasoning, and dynamic regulation of learning processes. Griffin and Care (2018) and Chai et al. (2024) frame these capacities as central components of twenty-first-century competence, positioning collaborative problem solving (CPS) as a key integrative skill that connects cognitive, social, and regulatory dimensions of learning.

In this thesis, learning is conceptualized as involving both individual and socially shared regulation. Self-regulated learning (SRL) refers to learners' ability to plan, monitor, and adjust their own learning processes, whereas socially shared regulation of learning (SSRL) extends this to collaborative contexts, where regulation is co-constructed through joint goal-setting, monitoring, and evaluation (Schraw et al., 2006; Zimmerman, 1995; Järvelä et al., 2016). These processes are central in collaborative inquiry settings, where learning occurs within pedagogically structured conditions that enable the coordinated interplay of individual and collective regulation.

This shift towards competence-oriented education has been reinforced by large-scale international initiatives. The OECD's Programme for International Student Assessment introduced CPS as a distinct assessment domain in 2015, thereby elevating collaboration to the level of core curricular outcomes alongside science, reading, and mathematics (OECD, 2017). In parallel, the Assessment and Teaching of 21st Century Skills project conceptualized CPS as a multidimensional construct comprising participation, perspective-taking, and social regulation, alongside task-focused cognitive processes (Care, 2018; Griffin & Care, 2015). Together, these initiatives have foregrounded collaboration and inquiry as essential for addressing complex, real-world scientific problems in educational settings.

Within science education, inquiry-based learning (IBL) has been widely promoted as a pedagogical approach aligned with these goals. As described by Shin et al. (2020) and Sun et al. (2022), IBL immerses students in practices that mirror authentic scientific work, including formulating research questions and hypotheses, designing and conducting investigations, analysing data, and constructing explanations. Digital technologies, particularly simulations, have further extended these possibilities by enabling learners to visualize abstract phenomena, manipulate variables, and explore dynamic systems that are otherwise inaccessible in physical classrooms (Feng & Wei, 2025; Olympiou & Zacharia, 2014).

When combined with collaborative dialogue, such environments offer the potential to support shared reasoning and collective knowledge construction.

Despite this strong theoretical and policy endorsement, the practical integration of collaboration, inquiry, and technology remains challenging. Burns et al. (2024) and Chai et al. (2024) note persistent definitional ambiguities surrounding collaborative skills, while Griffin and Care (2015) and Chai et al. (2024) highlight enduring difficulties in assessing complex social and cognitive processes reliably. From an implementation perspective, de Jong et al. (2021) document pedagogical barriers related to teachers' workload, confidence, and reliance on traditional instructional models, as well as technological constraints that complicate classroom enactment. Collectively, these challenges leave educators without clear, empirically grounded design principles for aligning learning goals, instructional activities, and assessment practices in collaborative inquiry contexts.

As a result, educators often struggle not only to design learning environments that balance task complexity, effective collaboration, and appropriate scaffolding, but also to support the real-time regulation of collaborative inquiry processes. Andrews-Todd et al. (2023) and Wang et al. (2025) emphasize that inquiry tasks frequently require the simultaneous coordination of cognitive, social, and technological demands, which can exceed learners' and teachers' capacity for monitoring and adaptative regulation. In the absence of technological tools that provide timely process-level information, teachers have limited visibility into which groups are struggling, disengaged, or operating off task, constraining their ability to offer targeted instructional support.

Taken together, these tensions reveal a fundamental educational problem: providing students with digital tools and collaborative opportunities does not automatically result in deep conceptual understanding or productive interaction. To address this gap between theoretical potential and classroom practice, the present thesis introduces the Technology-Enhanced Asymmetric Collaboration (TEAC) framework as a design-oriented approach for orchestrating the cognitive, social, and metacognitive mechanisms required for collaborative scientific inquiry.

Building on this perspective, asymmetric digital collaboration is defined as a pedagogical design in which learners hold distinct, non-overlapping information or controls within a shared digital environment, necessitating coordinated communication and mutual regulation to solve a common problem. Following the distinction articulated by Griffin and Care (2015), a clear separation is maintained between the pedagogical intervention and the targeted competence: asymmetric digital collaboration refers to the design strategy implemented through the TEAC framework, whereas CPS denotes the cognitive and social competencies that students enact and develop within that environment. Unlike symmetric collaboration, where learners have identical access to resources, asymmetric designs intentionally introduce an information gap to create positive interdependence. Empirical studies reviewed by Rojas et al. (2022) and Swiecki (2021) suggest that such role-based asymmetry can deepen interdependence by making each learner's contribution necessary for task completion, thereby supporting the

integration of cognitive and social processes and strengthening individual accountability (Çini et al., 2023; Ofstedal & Dahlberg, 2009).

Digital simulations provide a particularly suitable medium for operationalizing these principles. Meta-analytic evidence synthesized by Talan (2021) indicates that simulation-based learning is associated with substantial gains in academic achievement, while studies by Du et al. (2023) and Zhai et al. (2023) demonstrate positive effects on conceptual understanding and complex problem-solving skills. When embedded within collaborative inquiry designs, simulations can thus function not merely as content delivery tools but as structured environments for orchestrating interaction, distributing cognitive demands, and supporting metacognitive regulation.

The design of the TEAC framework is grounded in four complementary theoretical traditions. Social constructivism conceptualizes learning as the co-construction of knowledge through interaction and meaning negotiation (Brown et al., 1989; Cao, 2024; Stahl et al., 2005). Cognitive Load Theory (CLT) emphasizes the need to manage intrinsic and extraneous demands by aligning task complexity with working-memory capacity and distributing information across learners and tools (Du et al., 2023; Sweller, 1988, 2022). Principles from computer-supported collaborative learning (CSCL) inform the design of technological affordances that scaffold joint activity, communication, and regulation (Andrews-Todd et al., 2022; Hu & Chen, 2021; Jeong & Hmelo-Silver, 2016). And IBL frameworks structure these activities into iterative cycles of questioning, investigation, analysis, and reflection, supporting the integration of conceptual understanding and inquiry skills. Together, these theoretical perspectives inform the TEAC framework by specifying how cognitive load is managed, how interaction is structured, how regulation is supported, and how inquiry processes are sequenced.

In the TEAC framework, reflective scaffolds function as metacognitive supports for both self-regulated and socially shared regulation processes triggering learners' monitoring, evaluation, and regulation at both individual and group levels. First, embedded guidance and generic prompts support learners in identifying difficulties and adjusting strategies (Pei et al., 2020). Second, feedback mechanisms enable re-evaluation of task performance and metacognitive judgement (Çini et al., 2023). Finally, co-regulated content monitoring fosters socially shared regulation by aligning individual understanding with collective planning and decision-making during collaborative inquiry (Yang et al., 2024).

Central to this thesis is an explicit emphasis on face-to-face (F-F), human-to-human collaboration within authentic classroom settings. As noted by Chai et al. (2024), this mode of CPS offers the highest ecological validity but remains comparatively underexplored due to methodological and analytical constraints. By situating TEAC within this context, the present work seeks to contribute empirically grounded design principles for technology-enhanced, face-to-face collaborative inquiry in science education.

1.2. Aims and Research Questions

While social constructivism, CLT, CSCL, and IBL each offer valuable design principles, no unified model guides the orchestration of technology-mediated, F-F asymmetric collaboration in science education. Prior studies tend to isolate role scripting (Griffin & Care, 2015), reflective prompts (de Jong et al., 2021; Kolodner et al., 2003; Pedaste et al., 2015) or real-time analytics (Care et al., 2018) without examining their combined effects across varied group sizes, role structures, and task complexities. Consequently, educators lack empirically validated strategies for fostering deep conceptual understanding, robust CPS competencies, and metacognitive regulation within authentic collaborative inquiry. In response to this gap, the Technology-Enhanced Asymmetric Collaboration (TEAC) framework is introduced as an integrative design framework that synthesizes epistemological, cognitive, technological, and pedagogical perspectives, with each theoretical component serving a distinct and complementary function within the overall design. Taken together, the aims of this thesis are guided by the assumption that technology-mediated collaboration in science learning requires structurally enforced interdependence through asymmetrical design. However, such design alone is insufficient for deep inquiry learning unless it is complemented by explicit metacognitive scaffolding, such as structured reflection protocols.

Aim: The central aim of this thesis is to design, implement, and empirically examine the Technology-Enhanced Asymmetric Collaboration (TEAC) framework as a pedagogical design for inquiry-based science learning in authentic science classrooms settings. The TEAC framework is developed to support conceptual understanding, collaborative problem-solving competencies, and metacognitive regulation by systematically orchestrating group configuration, structured role asymmetry within digital simulations, and embedded reflective scaffolding. Through a sequence of design-based studies, this thesis investigates how these interrelated design dimensions create the conditions that support and structure students' cognitive, social, and regulatory processes during collaborative inquiry.

Research Questions: To explore TEAC's promise, three core research questions (RQs) guided a three-phase Design-Based Research (DBR) sequence, each phase focusing on a distinct simulation context: photosynthesis, electricity, and genetics, and collectively refining the framework over successive iterations:

1. RQ1: Group Configuration
   How does group size influence students' inquiry performance and collaborative dynamics in technology-enhanced asymmetric simulation tasks?
   Investigating group size served as the foundational step to determine the optimal configuration for the TEAC framework before focusing on role asymmetry. This question served as the primary focus of Phase I (Photosynthesis),

which contrasted dyadic (two person) with larger (four person) team configurations to examine how task distribution shapes conceptual engagement and peer interaction.

2. RQ2: Collaborative Interaction
   How does structured role asymmetry influence students' ability to co-construct knowledge and solve problems collaboratively?
   Investigated across all three phases, this question underpins TEAC's core design principle. Each subsequent study, Phase II (Electricity) and Phase III (Genetics), refined and extended the initial role allocations to new content domains and technological media, probing their effects on dialogue, negotiation, and mutual support.

3. RQ3: Regulation Through Reflection
   How do reflective practices and digital prompts support students' metacognitive regulation during collaborative inquiry?
   Explored progressively, this question evolved from implicit, end-of-task debriefs in Phase I, to structured post-task reflections in Phase II, and ultimately to a mature "Remember–Recall–Learning" (RRL) protocol in Phase III. This trajectory allowed the thesis to trace how reflection scaffolds can be woven increasingly deeply into the TEAC cycle.

Each DBR cycle employed mixed methods, combining quantitative rubric-scored artifacts and ATC21S CPS surveys with qualitative structured reflections and teacher debriefs, which grew in sophistication across iterations. This triangulated design ensured that TEAC remained both theoretically sound and finely attuned to real-world classroom dynamics.

1.3. Overview of the TEAC Framework

The TEAC framework operationalizes IBL in science classrooms by orchestrating three complementary "learning gears" (cognitive, social, and metacognitive) coordinated through pedagogical design that guide students through authentic, problem-driven investigation, collaborative sense-making, and reflective regulation (Figure 1). The central element of the model does not represent an additional learning process, but a pedagogically designed configuration that structures the conditions for learning. In the TEAC framework, this configuration takes the form of an asymmetric collaborative inquiry scenario, where structured role asymmetry, information gaps, and task design activate and sustain cognitive, social, and metacognitive processes. These processes are not directly connected in a linear or mechanical manner; instead, their interaction is mediated through the pedagogical design, enabling their dynamic interplay.

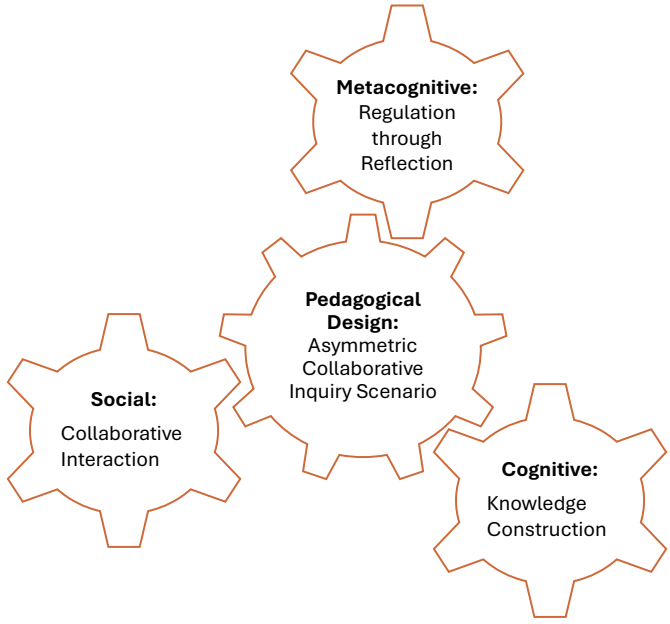

Figure 1. *Conceptual Diagram of the Theoretical Framework*

In the cognitive gear, each learner controls distinct variables or informational views, reflecting IBL's emphasis on inquiry, experimentation, and hypothesis generation. Learners must negotiate and co-construct explanations to refine shared mental models (Jeong & Hmelo-Silver, 2016; Kolodner et al., 2003). The social gear translates IBL's principle of collaborative knowledge construction into practice by combining several design elements.

In this framework, a clear conceptual distinction is maintained: cognitive processing refers to the individual learner's sense-making of the data they control, while social interaction involves the coordination and negotiation between peers. Co-construction of knowledge refers to the process in which individual cognitive contributions are integrated through social interaction into a shared understanding. This integration is not a direct mechanical overlap but is mediated through the pedagogical design, which creates the conditions for aligning individual and shared understanding.

Asymmetric tasks create interdependent roles through the deliberate distribution of control or information, while shared digital workspaces, such as online laboratories and simulations, allow partners to observe each other's actions in real time. Structured prompts and teacher guidance further support these activities, together scaffolding key collaborative processes including negotiation, perspective-taking, and transactive dialogue around data and concepts (Andrews-Todd et al., 2022; Popov et al., 2018). The metacognitive gear integrates teacher-guided scaffolding and structured reflection tasks to foster learners' self-regulation and problem-solving abilities. It employs guided worksheets with open-ended questions and teacher-led class discussions to prompt students to evaluate

their responses and analyse their collaboration. In doing so, students monitor and assess both their individual reasoning strategies and their collective problem-solving processes. This approach strengthens metacognitive and socio-metacognitive awareness and supports conceptual development and group regulation (Lazonder & Harmsen, 2016; Pei et al., 2020; Pöysä-Tarhonen et al., 2022; Wang et al., 2025). These metacognitive scaffolds prompt students to set goals, detect and correct errors in real time, and elaborate on emerging hypotheses (Denton & Ellis, 2023; Wang et al., 2025). Concurrently, collaboration scripts and group-awareness tools foster socially shared regulation. Through these tools, teams co-construct monitoring standards, negotiate regulatory strategies, and jointly evaluate outcomes to guide subsequent inquiry (Järvelä et al., 2016; Yang et al., 2024). This entire process is underpinned by four pedagogical priorities: positive interdependence, iterative theory–practice alignment, reflective metacognition, and adaptive task design. Overall, the TEAC framework integrates these elements into a coherent pedagogical design that systematically supports conceptual understanding, collaborative problem-solving, and self-regulated learning in science education.

2. THEORETICAL FRAMEWORK

The TEAC framework is grounded in four complementary theoretical traditions: social constructivism, CLT, computer-supported collaborative learning, and inquiry-based learning. These traditions were selected because, together, they address the epistemological, cognitive, technological, and pedagogical requirements of technology-enhanced collaborative inquiry, which no single framework can sufficiently capture on its own. In this synthesis, each theoretical component serves a specific function. Social Constructivism provides the epistemological goal of collaborative knowledge co-construction, while CLT provides the design constraint of managing split-attention via asymmetric interfaces. Furthermore, CSCL provides the technological medium through shared workspaces and scripts, and IBL provides the pedagogical sequence of hypothesis, experimentation, and reflection. Together, they form an integrated design logic. Within this logic, learning goals, task structure, technological affordances, and instructional sequencing are coherently aligned with the ATC21S model of Collaborative Problem Solving to activate its three interlocking learning gears.

Within this framework, CLT functions as a design-informing explanatory lens rather than as a construct subjected to direct empirical measurement; accordingly, references to cognitive load denote theoretically grounded design intentions and inferred behavioural manifestations rather than psychometric or physiological assessment. Drawing on Vygotsky's socio-cultural theory, TEAC assigns asymmetric roles that compel learners to externalize reasoning and negotiate understanding, transforming private cognitions into collaboratively constructed knowledge (Brown et al., 1989; Vygotsky, 1980). CLT informs TEAC's division of simulation variables across dyads, intended to reduce extraneous processing through integrated interfaces and to direct working-memory resources towards germane schema construction (Kalyuga et al., 2003; Sweller, 1988). From the CSCL perspective, context-sensitive digital scaffolds, segmented displays, shared visualizations, and process-aware feedback, structure interaction routines that foster perspective-taking, transactive dialogue, and mutual regulation (Jeong & Hmelo-Silver, 2016; Stahl et al., 2005). IBL principles are realized by embedding students in authentic, problem-driven tasks that guide them through questioning, hypothesis generation, experimentation, and explanation, with role responsibilities mapped onto each inquiry phase (Kolodner et al., 2003; Pedaste et al., 2015). In this context, inquiry performance refers to students' demonstrated application of inquiry processes within specific tasks, as reflected in their task engagement and problem-solving processes. References to inquiry skills are used to denote the underlying competencies these performances draw upon, rather than independently measured, transferable abilities. Moreover, by drawing on the ATC21S CPS framework's multidimensional construct of participation, perspective-taking, and social regulation, TEAC's dialogic prompts, role structures, and metacognitive assessments operationalize 21st-century collaboration within science inquiry (Ahonen & Harding, 2018; Wu et al., 2021). Together, these

foundations ensure that TEAC's orchestrated gears, Knowledge Construction, Collaborative Interaction, and Regulation Through Reflection, are intended to synergistically promote deep conceptual understanding, robust collaborative competencies, and sustained self-regulated learning.

Although IBL is widely promoted in educational policy and research, evidence from large-scale assessments and research syntheses indicates that its classroom implementation is often challenging and yields variable outcomes. Analyses within the OECD and PISA frameworks show that frequent inquiry activities are not consistently associated with higher achievement and, in some contexts, display a negative or curvilinear relationship with science performance when inquiry is insufficiently guided or structured (OECD, 2013, 2017). These findings suggest that the effectiveness of inquiry-based approaches is contingent on instructional design rather than inherent to inquiry itself.

Research in science education further demonstrates that poorly structured inquiry can lead to high levels of observable student activity without corresponding conceptual learning. Mayer (2004) shows that unassisted discovery places substantial demands on working memory, particularly for novice learners, while Hofstein and Lunetta (2004) document how laboratory activities often emphasize procedural completion over conceptual understanding. From a CLT perspective, Sweller (1988) explains that unguided problem solving relies on means–ends analysis that consumes working-memory resources needed for schema acquisition, a limitation further elaborated by Kirschner, Sweller, and Clark (2006) and by Sweller's (2022) distinction between biologically primary and secondary knowledge.

These challenges are amplified in collaborative and digital inquiry contexts, where learners must coordinate social interaction, task demands, and technological tools simultaneously. Barron (2005) argues that collaborative activity may remain procedural rather than epistemically productive, a distinction empirically reinforced by Premo et al. (2022), who demonstrate that surface interaction does not predict learning gains. At the instructional level, Jeong and Hmelo-Silver (2016) highlight increased orchestration demands and limited teacher visibility in technology-enhanced collaborative learning environments. Policy analyses similarly point to a persistent theory–practice gap, whereby inquiry-oriented pedagogies are often successfully enacted only by expert teachers and lose fidelity when scaled to typical classrooms due to time constraints and monitoring challenges (Lazonder & Harmsen, 2016; OECD, 2013).

Importantly, these critiques do not reject IBL but rather indicate that inquiry is most effective when it is explicitly guided and structurally supported (de Jong et al., 2023; Hmelo-Silver et al., 2007). Within this perspective, the TEAC framework is proposed as a design response that integrates role asymmetry, guided interaction, and technological scaffolds to distribute cognitive demands, enforce interdependence, and render collaborative inquiry processes more visible and manageable in authentic classroom contexts.

2.1. Core Learning Process 1: Knowledge Construction

In the TEAC framework, knowledge construction refers to the cognitive processes through which learners develop both conceptual understanding and inquiry knowledge. This process is driven by students' inquiry performance – their active application of scientific methods, such as testing hypotheses and interpreting data, to build accurate mental models. To support this cognitive work, knowledge construction in TEAC is explicitly grounded in Cognitive Load Theory (CLT), with the design intention of helping learners devote mental resources to scientific reasoning rather than interface navigation (Sweller, 1988, 2022). First, TEAC's interfaces consolidate controls and feedback into a single, shared workspace. For example, interface elements such as variable controls and real-time feedback are co-located within a unified display, reducing the need to shift attention between separate panels and thereby minimizing split-attention effects (Guzmán & Zambrano, 2024; Orbegoso-Dávila et al., 2024). Second, TEAC enacts a dyadic "extended cognitive workspace" by assigning each partner complementary controls while presenting the unified outcome to both. In such environments, learners are assigned complementary control over task-relevant variables while jointly observing shared outcomes, enabling them to focus cognitive resources on interpreting causal relationships rather than coordinating fragmented information sources.

Finally, TEAC leverages the expertise-reversal effect by offering worked-example guidance to novices while progressively reducing support for more experienced learners, thereby balancing intrinsic load and maximizing schema construction (Kalyuga et al., 2003). Through these integrated interfaces, shared cognitive workspaces, and adaptive scaffolds, TEAC is intended to minimize extraneous demands, capitalize on distributed cognitive resources, and support learners in constructing robust scientific understanding.

2.2. Core Learning Process 2: Collaborative Interaction

Central to the TEAC framework is the premise that science learning occurs within deliberately structured collaborative environments, designed to enable face-to-face interaction rather than isolated activity. Grounded in Vygotsky's Zone of Proximal Development and social constructivist principles (Brown et al., 1989; Pea, 1993; Vygotsky, 1980), TEAC allocates complementary but distinct roles to partners, creating an "information gap" that mandates peer negotiation. In such environments, one learner controls a subset of task-relevant variables while the other manages complementary elements.

Progression in these tasks is enabled by pedagogical designs that require students to articulate and reconcile their observations, thereby embedding collaboration at the core of the inquiry process. Here, collaborative interaction is structured as a key component within the pedagogical design that enables coordination, whereas the co-construction of knowledge is the targeted outcome,

representing the pedagogically mediated integration of individual cognitive contributions are integrated into a unified, collectively owned mental model.

Scaffolding Interaction Through Scripts. To channel collaborative efforts towards deep CPS, TEAC employs explicit interaction scripts, including turn-taking rules, shared digital workspaces, and structured prompts, that guide students into negotiation, perspective-taking, and transactive communication (Jeong & Hmelo-Silver, 2016; Rojas et al., 2022). In such designs, learners may be intentionally provided with non-overlapping access to information, requiring them to articulate their observations verbally and coordinate their understanding through dialogue. Such an asymmetric design was fundamental for aligning students' mental models and fostering a deeper co-construction of knowledge.

Fostering Positive Interdependence and Accountability. These structurally distributed, asymmetric designs are considered to create the positive interdependence, mutual accountability, and peer monitoring essential for authentic CPS. TEAC's collaborative design aligns with the ATC21S framework's dimensions of participation, perspective-taking, and social regulation (Griffin & Care, 2015) and draws on Van den Bossche et al.'s (2006) work on role-based interdependence. While grounded in ATC21S, these dimensions align with recent systematic evidence identifying socio-cognitive exchange, socio-emotional interdependence, and group regulation as the defining characteristics of productive peer collaboration (Baucal et al., 2023). By ensuring that no student can complete the task alone, TEAC embeds these social demands directly within the learning activity, narrowing the gap between collaborative theory and classroom practice.

Collaboratively Editable Interfaces in TEAC make student reasoning transparent, enforce interdependence, and reduce extraneous load by unifying all controls, outcomes, and feedback within a single, shared workspace. This integrated environment serves as a persistent "group memory," anchoring negotiation, co-interpretation, and iterative refinement of scientific schemas.

Such environments can capture learner actions and evolving representations, providing a basis for analysing cognitive and social processes during collaborative inquiry (Andrews-Todd et al., 2022; Hu & Chen, 2021; Ouyang et al., 2022; Swiecki, 2021). Inline metacognitive prompts further require students to externalize and justify their decisions in real time, scaffolding reflection-in-action by guiding them to articulate hypotheses and evaluate evidence as they work (Pea, 1993; Wang et al., 2021).

True collaborative engagement occurs when no individual can advance the task alone (Burns et al., 2024; Docherty, 2020). TEAC achieves this by assigning complementary yet distinct controls or informational views to each partner, across different dimensions of the task, so that dyads must coordinate continuously (Care, 2018; Du et al., 2023). Procedural constraints that require articulation of individual perspectives and shared workspaces make each contribution explicit, embedding negotiation and perspective-taking into every interaction (Lu & Bulut, 2024).

According to CLT, instructional designs should eliminate unnecessary processing demands so learners can devote resources to schema construction (Orbegoso-Dávila et al., 2024; Sweller, 1988). TEAC's interfaces embed labels,

controls, and dynamic displays within one view designed to mitigate split-attention effects and reduce the need for separate legends or menus (Guzmán & Zambrano, 2024; Wang et al., 2025). Shared visual organizers and on-screen transcripts of key findings keep all essential information within the dyad's collective workspace, optimizing working-memory use for critical inquiry tasks (Orbegoso-Dávila et al., 2024).

Persistent external artifacts, charts of trial outcomes, dynamic diagrams, and logged parameter changes serve as "group memories" that learners can revisit to support reflection (Jeong & Hmelo-Silver, 2016; Schraw et al., 2006). Such artifacts may take different representational forms that maintain shared context across inquiry episodes. By preserving records of past decisions, these durable representations help students align their evolving mental models and sustain coherent, cumulative inquiry over time (Care, 2018; Pea, 1993).

2.3. Core Learning Process 3: Regulation Through Reflection

Regulation Through Reflection integrates principles from Self-Regulated Learning (SRL) theory and Socially Shared Regulation of Learning (SSRL) to guide students in monitoring, evaluating, and adapting both their scientific reasoning and collaborative processes. SRL theory characterizes regulation as intentional, goal-directed metacognitive activity in which learners plan, monitor, and adjust their own thinking and strategies (Schraw et al., 2006; Zimmerman, 1995). SSRL extends this view to small-group contexts, highlighting how peers co-construct goals, share monitoring responsibilities, negotiate plans, and jointly evaluate outcomes (Järvelä et al., 2016; Yang et al., 2024). Research on technology-mediated collaborative learning shows that challenges in group work extend beyond cognitive task coordination to include the regulation of participation, roles, and interaction processes, which do not reliably self-organize through collaboration alone (Channa et al., 2025). Empirical evidence indicates that such regulatory processes often require deliberate pedagogical and technological support, as students tend to need external scaffolding to develop shared regulation strategies and to prevent the emergence of unequal or peripheral participation roles (Latva-aho et al., 2025). This perspective aligns with the present thesis' emphasis on reflective regulation as a designed component of technology-enhanced asymmetric collaboration, intended to make otherwise implicit interactional and motivational challenges visible and regulatable (Näykki et al., 2021). In TEAC, reflection is scaffolded through a combination of written worksheets, structured prompts, and teacher-facilitated discussion, progressively evolving from brief, implicit activities towards more structured and extended reflection phases across design iterations. To clarify the relationship between these pedagogical supports and the learning process, a distinction is made in this thesis between external scaffolds and internal regulatory processes. Reflective practices refer to the pedagogical tools and supports provided to students (e.g. worksheets,

teacher-led debriefs, and the RRL protocol), whereas metacognitive regulation refers to learners' internal processes of planning, monitoring, and evaluating both task performance and collaboration that these practices are designed to elicit. The term metacognitive engagement is therefore used descriptively to denote students' observable involvement in these regulatory processes rather than as a separately defined or independently measured construct.

The inclusion of extended, structured reflection represents a departure from typical classroom practice, where debriefs rarely extend beyond a few minutes. When reflection is systematically integrated into instructional design, TEAC enables learners to engage in deep self-evaluation, reconstructing and reconciling their initial ideas with new evidence (Denton & Ellis, 2023; Pei et al., 2020) and participating in rich peer dialogues that tests and refines emerging ideas (Çini et al., 2023; Jurkowski et al., 2024). Crucially, such structured reflection also enables teachers to deliver precise, context-sensitive feedback, ranging from strategic questioning to structured debrief prompts, which directly scaffolds students' metacognitive processes (Denton & Ellis, 2023; Halttunen et al., 2023). These targeted interventions not only deepened learners' self-regulatory judgments but also modeled corrective actions that highlighted overlooked variables, refined experimental designs, and promoted iterative improvement of both conceptual explanations and collaborative interactions (Griffin & Care, 2015; Kolodner et al., 2003; H.-S. Wang et al., 2021).

2.4. Pedagogical Design Priorities: Role Distribution, Digital Scaffolds and Assessment

The translation of TEAC from theory into classroom practice rests on three interlocking design priorities, each of which is deeply grounded in the broader literature on collaborative learning.

Role Distribution. Structured role distribution in TEAC assigns each learner unique controls and responsibilities, thereby creating an information gap that mirrors real-world "jigsaw" problems and mandates authentic verbal negotiation and coordinated decision-making. Griffin and Care (2015) describe how asymmetric access to task elements forces students to share and integrate individually held data, while Stahl et al. (2005) and Van den Bossche et al. (2006) emphasize that such interdependence drives joint planning and consensus building. Burns et al. (2024) further note that partners must explicitly question one another and reconcile differing perspectives to advance their shared goals. This design instils positive interdependence; no learner can complete the task alone and it counteracts the risks of social loafing and unilateral decision-making. Nonetheless, Care et al. (2018), Li et al. (2025), and Premo et al. (2022) warn that role asymmetry alone does not guarantee balanced participation; without additional scaffolds such as collaboration scripts, teacher monitoring, or participation-awareness in shared workspaces, stronger students may dominate while others disengage (He et al., 2023; Lertcharoenrit, 2020; Vuorenmaa et al., 2024). These

principles are operationalized through domain-specific role configurations and task structures, as described in detail in Chapter 3.

Nonetheless, role asymmetry alone does not guarantee balanced participation. Without additional supports, some learners may disengage or relinquish responsibility, allowing more assertive peers to dominate (Lertcharoenrit, 2020). Moreover, the cognitive demands of interdependent tasks can overwhelm less experienced students unless appropriate scaffolds are provided (Orbegoso-Dávila et al., 2024). To counteract these tendencies, in-class monitoring and timely, individualized feedback are essential for drawing quieter students into the dialogue (He et al., 2023). Tools that make participation levels transparent, such as group-awareness dashboards, have also been shown to curb free-riding by signalling when contributions are uneven (Vuorenmaa et al., 2024). Even with well-designed dyads, partners may disengage without occasional teacher intervention to redistribute responsibilities or renew focus (Thomason & Hsu, 2025).

Digital Scaffolds. TEAC's simulations incorporate segmented controls, in-situ labels, shared visualizations, progress indicators, and contextual prompts to regulate both cognitive and social load. By externalizing routine processes, such as tracking variable settings, to the interface, these socio-cognitive tools free learners' working-memory capacity for germane reasoning and collaborative schema construction (Kalyuga et al., 2003; Orbegoso-Dávila et al., 2024; Schraw et al., 2006). Shared visual workspaces ensure partners maintain a common view of outcomes, ensuring a shared representation of task outcomes, thereby anchoring negotiation and joint interpretation (Jeong & Hmelo-Silver, 2016; Zhai et al., 2023). Collectively, these embedded features distribute cognitive load across group members, support metacognitive regulation, and foster socially shared regulation, enabling students to focus on higher-order problem solving and the co-construction of robust knowledge frameworks (Guzmán & Zambrano, 2024; Weng & Ren, 2025).

Triangulation of Assessment Data

TEAC's evaluation strategy employs methodological triangulation by integrating three complementary assessment methods: analytic rubrics, self-report surveys, and coded reflection artifacts. This multi-perspective approach is designed to capture the complex co-occurrence of cognitive, social, and metacognitive dimensions as shaped through pedagogical design, which together define productive CPS (Baucal et al., 2023; Pöysä-Tarhonen et al., 2022). First, analytic rubrics grounded in established frameworks (Care, 2018; Griffin & Care, 2015) are applied to students' written worksheet responses and interaction logs. These rubrics specify clear criteria for subject knowledge, inquiry processes, and discourse quality, enabling precise measurement of the quality of task strategies and solutions (Baucal et al., 2023). Second, immediately after each task students complete a CPS Skills Questionnaire adapted from the ATC21S framework (Cheruiyot & Molnár, 2025; Çini et al., 2023; Hesse et al., 2015). This self-report instrument probes perceptions of participation, perspective-taking, social regu-

lation, and interdependence, offering insight into learners' metacognitive and attitudinal dimensions alongside rubric scores. Finally, coded reflection artifacts, including structured post-task prompts, learning journals, and transcribed debrief discussions, are analysed using the three-step RRL protocol (Schraw et al., 2006). This systematic analysis reveals how students monitor, evaluate, and adjust both individual reasoning and joint problem-solving processes, and it complements rubric and survey data by illuminating students' metacognitive regulation processes. By triangulating these three data streams, TEAC enhances the validity of its findings and provides a robust foundation for targeted instructional refinements.

2.5. Operationalizing TEAC: Conceptual Overview of Three DBR Cycles

This thesis conceptualizes the Technology-Enhanced Asymmetric Collaboration (TEAC) framework as an iteratively refined pedagogical model, developed through successive Design-Based Research (DBR) cycles rather than as a fixed instructional intervention. Operationalizing TEAC therefore involves examining how its core theoretical principles are progressively instantiated, tested, and refined in response to both empirical evidence and classroom constraints.

Throughout the thesis, TEAC is structured around three interrelated pedagogical functions, referred to as "learning gears":

(1) support for knowledge construction through inquiry-based tasks,

(2) social scaffolding via asymmetric role distribution and interdependence, and

(3) metacognitive regulation through structured reflection.

These gears provide a conceptual lens for understanding how pedagogical design supports and coordinates cognitive, social, and metacognitive learning processes in technology-enhanced collaborative inquiry environments.

Rather than assuming that these design principles operate uniformly across contexts, the thesis adopts a DBR logic in which each design cycle foregrounds different aspects of the framework. Early cycles focus on establishing viable configurations of asymmetric collaboration and identifying design tensions, while later cycles refine interaction quality and introduce more explicit regulatory supports. In this sense, TEAC is treated as a developmental construct, whose operational form emerges through systematic iteration rather than being fully specified a priori.

At the theoretical level, this approach enables the framework to remain responsive to classroom realities while retaining coherence across studies. At the methodological level, it supports alignment between theoretical constructs and empirical measures without conflating conceptual exposition with procedural detail. The empirical instantiation, iterative refinement, and validation of TEAC across three DBR cycles are presented in detail in Chapter 3, where the design logic, study protocols, and analytical approaches are systematically documented.

3. RESEARCH METHODOLOGY

This chapter presents the methodological framework through which the Technology-Enhanced Asymmetric Collaboration (TEAC) framework was empirically examined and refined. Building on the theoretical foundations outlined in Chapter 2, the chapter describes how the central learning processes of the TEAC framework were translated into concrete research designs, data collection strategies, and analytic procedures across three design-based research studies.

This thesis adopts a Design-Based Research approach, which is particularly suitable for studies that aim to refine educational interventions through iterative cycles of design, enactment, and analysis in real-world contexts (Barab & Squire, 2004; Collins et al., 2004)**.** This methodological orientation aligns with the goals of the present research, as the intention is not only to examine learning outcomes but also to progressively improve a pedagogical design under authentic curricular and classroom constraints. Rather than treating Studies I–III as independent investigations, the chapter conceptualizes them as consecutive design-based research cycles addressing complementary aspects of the same pedagogical framework.

The three core learning processes of the TEAC framework, namely knowledge construction, collaborative interaction, and regulation through reflection, serve as the organizing logic for methodological choices across all studies. These learning processes guided the design of asymmetric roles and digital tools, the integration of reflective scaffolds, and the selection of assessment and analysis methods. To capture both learning outcomes and the processes through which technology-enhanced collaboration unfolds, the design-based research approach is complemented by a mixed-methods research design that integrates quantitative and qualitative data sources (Creswell & Plano Clark, 2018).

To support an overview-oriented reading of the methodology, Figure 2 and Table 1 are positioned at the beginning of this chapter. Figure 2 provides a conceptual reading guide by illustrating the progressive design logic of the study and the alignment between research questions, design dimensions, and the three DBR cycles. Table 1 then functions as an integrative methodological map, summarizing how each research question is addressed across Studies I–III, which learning dimensions are foregrounded in each study, and how data sources, instruments, and analytic approaches are aligned with the TEAC framework.

The primary function of Table 1 is to reduce redundancy by consolidating methodological information that would otherwise be repeated across study-specific sections. Readers are therefore directed to Table 1 for an overview of the research questions, learning dimensions, instruments, and analytic procedures, while the subsequent sections focus on the design logic, procedural implementation, and methodological decisions specific to each DBR cycle.

Following this overview, the chapter first outlines the design-based research framework and its application within the TEAC context. It then describes the study contexts and participants, followed by the data sources, instruments, and analytic procedures used across the three studies. The chapter concludes with a

discussion of methodological quality, reliability, trustworthiness, and ethical considerations, demonstrating how the theoretical principles introduced in Chapter 2 were systematically operationalized and examined in authentic classroom settings.

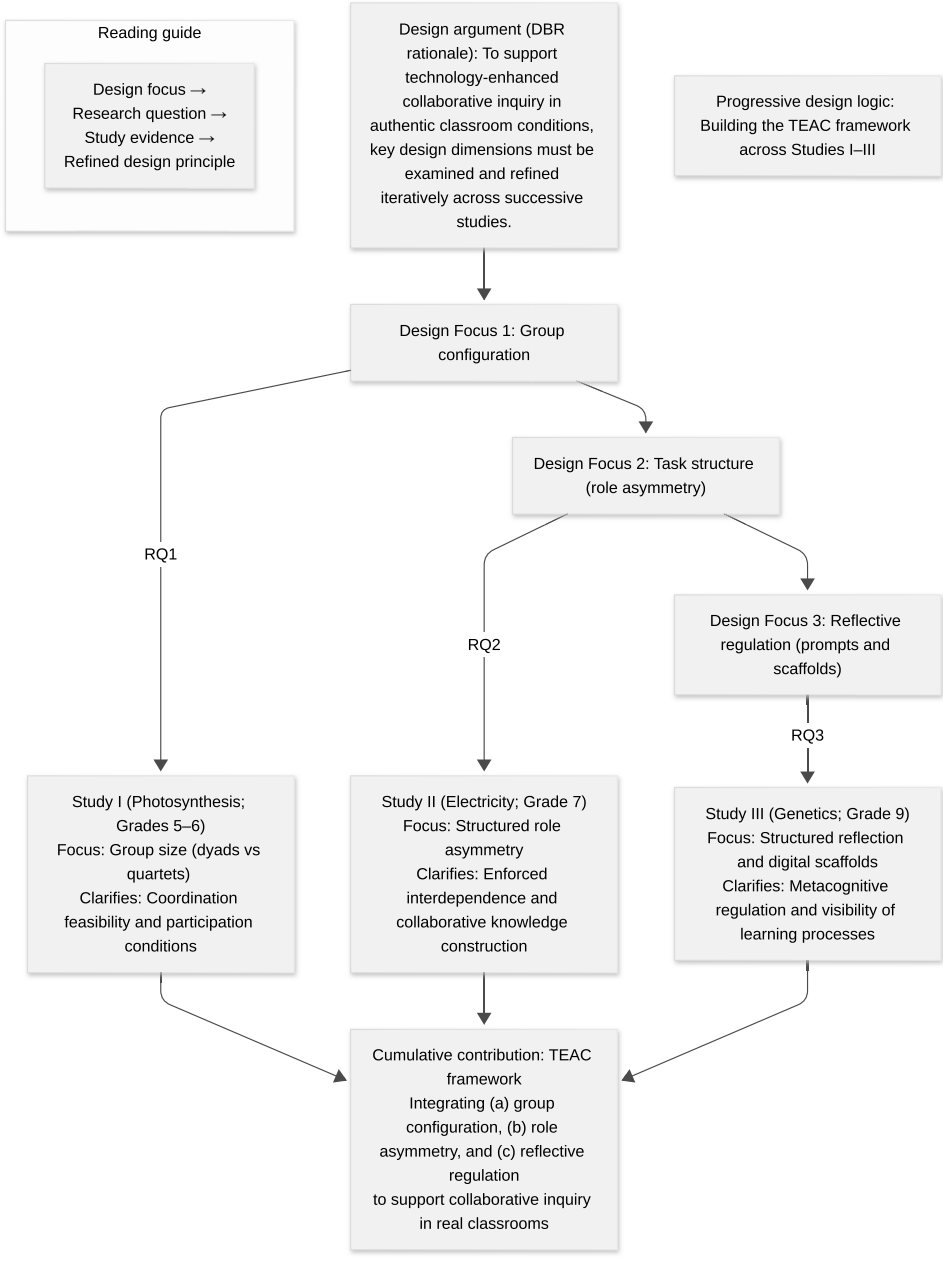

Figure 2. *Progressive design logic of the TEAC framework across three DBR cycles. The figure illustrates how successive design dimensions (group configuration, task structure through role asymmetry, and reflective regulation) were examined through Research Questions RQ1–RQ3 and empirically refined across Studies I–III. The visual serves as a reading guide for Chapter 3, highlighting the cumulative development of the TEAC framework through iterative design-based research.*

Table 1. *Alignment of the Research Questions, Conceptual Learning Dimensions, Study Contexts, Data Sources, and Analytic Approaches Across Studies I–III*

Research Question	Learning Dimension	Study and Participants	Data Source	Main Analysis and Quality Indicators
RQ1. How does group size influence students' inquiry performance and collaborative dynamics in technology-enhanced asymmetric simulation tasks?	Inquiry performance	Study I: Photosynthesis Digital Lab; Grades 5–6; public school in Tartu, Estonia; 5th grade N = 58 (M age = 11.3), 6th grade N = 74 (M age = 12.4); group configurations: dyads and quartets	Open-ended inquiry tasks focusing on effects of light intensity and seasonal changes in photosynthesis[1]	Rubric-based scoring (0–2); interrater reliability κ = .76–.84; Mann–Whitney U tests for group-size comparisons
	Perceived collaboration quality	Study I	4-item collaboration questionnaire (7-point Likert scale; information sharing, team support, collective learning)[1]	Internal consistency α = .80 (Grade 5) and α = .83 (Grade 6); Mann–Whitney U tests
	Collaboration-related difficulties	Study I	Qualitative analysis of inquiry task responses[1]	Error categorization (syntax, collaboration, inquiry); interrater reliability κ = .73
RQ2. How does structured role asymmetry influence students' ability to co-construct knowledge and solve problems collaboratively?	Subject knowledge	Study II: Electricity Digital Lab; Grade 7; N = 47 (M age = 13.8, SD = 0.34); 19 pairs and 3 triplets; Study III: Genetics Digital Lab; Grade 9; N = 43 (M age = 15.7, SD = 0.34); 17 pairs and 3 triads	Open-ended worksheet questions assessing domain-specific content knowledge (Study II: electric circuits; Study III: K1 basic inheritance, K2 abstract genetics)[2,3]	Rubric-based scoring; Study II: correct (1), partially correct (0.5); Study III: 3-point rubric (high, average, low); descriptive statistics
	Inquiry knowledge (identifying and relating variables)	Study II and Study III	Open-ended worksheet questions requiring identification and reasoning about independent and dependent variables (Study II; Study III K3) [2,3]	Rubric-based scoring; descriptive statistics
	CPS participation	Study II and Study III	CPS questionnaire (10 items, 5-point Likert scale; ATC21S-based) [2,3]	Descriptive statistics; reliability α = .779 for participation (Study III)

Research Question	Learning Dimension	Study and Participants	Data Source	Main Analysis and Quality Indicators
	CPS perspective-taking	Study II and Study III	CPS questionnaire (ATC21S-based items) [2,3]	Descriptive statistics; interpreted through triangulation due to low subscale reliability
	CPS social regulation	Study II and Study III	CPS questionnaire (ATC21S-based items) [2,3]	Descriptive statistics; supported by reflection and observation data
	CPS interdependence	Study II and Study III	CPS questionnaire (interdependence items adapted from Van den Bossche et al.) [2,3]	Descriptive statistics; interpreted cautiously as a relational learning dimension
RQ3. How do reflective practices and digital prompts support students' metacognitive regulation during collaborative inquiry?	Metacognitive regulation (Remember–Recall–Learning)	Study III: Genetics Digital Lab; Grade 9; N = 43; reflection design informed by Study II	Post-task open-ended reflection prompts[3]	RRL coding (Remember: recall accuracy; Recall: judgment accuracy; Learning: conceptual development); frequency analysis
	Reflective evaluation of collaboration	Study II and Study III	Embedded worksheet reflections (Study II); post-task reflections and teacher-facilitated discussions (Study III); classroom observations [2,3]	Qualitative content analysis and thematic coding; triangulation across data sources
	Perceived collaboration benefits	Study III	Reflection prompts and CPS questionnaire items addressing perceived usefulness of collaboration[3]	Spearman correlation between perceived benefits and combined subject and inquiry knowledge scores ($r = .42$, $p < .05$)

Note. The numerals in the Data Source column indicate the originating empirical studies: 1 = Study I, 2 = Study II, 3 = Study III. Comprehensive descriptions of the data sources, including research design, participants, instruments, and analytical procedures, are provided in the respective published article. Learning dimensions represent conceptual constructs guiding the research questions, whereas the listed instruments and data sources represent operational indicators used to examine these constructs in the empirical studies. Reliability coefficients and interrater agreement values are reported where applicable.

3.1. Design-Based Research Framework and Methodological Rationale

This thesis is grounded in a design-based research framework, which is particularly appropriate for investigating complex learning processes situated in authentic educational contexts. Design-based research is characterized by iterative cycles of design, enactment, analysis, and refinement, through which both theoretical understanding and practical solutions are developed in parallel (Barab & Squire, 2004; Collins et al., 2004). In contrast to experimental approaches that prioritize controlled conditions, design-based research foregrounds ecological validity and recognizes classroom constraints as integral to the research process.

Within this thesis, the design-based research framework serves two complementary purposes. First, it provides a systematic approach for examining how technology-enhanced asymmetric collaboration supports inquiry learning and collaborative problem-solving in school science. Second, it enables the progressive refinement of the TEAC framework through empirical feedback obtained across multiple classroom implementations. Rather than aiming to test a fixed intervention, the research seeks to understand how specific design principles function in practice and how they can be adapted to better support learning processes over time.

The three studies included in the thesis represent consecutive design-based research cycles, each building on insights from the preceding cycle. Study I focused on the role of group size in asymmetric collaborative inquiry, providing initial evidence on inquiry performance and perceived collaboration quality. Study II extended this work by introducing structured role asymmetry and by examining collaborative problem-solving processes and inquiry-related reasoning in greater depth. Study III further refined the design by integrating systematic reflective scaffolds to support metacognitive regulation during collaborative inquiry. Together, the studies form a coherent methodological progression rather than isolated empirical cases.

Across all design cycles, methodological decisions were guided by the central learning processes articulated in the TEAC framework. Knowledge construction, collaborative interaction, and regulation through reflection informed the design of learning tasks, the distribution of roles and information, the integration of digital tools, and the selection of data sources. This alignment ensured that methodological choices remained theoretically grounded while allowing flexibility for iterative adaptation based on empirical findings.

To capture both learning outcomes and learning processes, the design-based research framework was complemented by a mixed-methods approach. Quantitative data were used to examine patterns in inquiry performance, subject and inquiry knowledge, and self-reported collaborative processes, while qualitative data provided insight into students' reasoning, interaction, and reflective regulation. The integration of multiple data sources supported triangulation and strengthened the interpretive robustness of the findings (Creswell & Plano Clark, 2018).

Table 2. *Evolution of the TEAC Framework Across Three DBR Cycles*

Design Feature	Study I: Photosynthesis (Grades 5–6)	Study II: Electricity (Grade 7)	Study III: Genetics (Grade 9)	Rationale for Evolution
Group Configuration	Comparative: Dyads (2) vs. Quartets (4).	Dyads (with occasional Triads for logistics); no size comparison.	Dyads (with occasional Triads); no size comparison.	Study I indicated dyads produced fewer errors and higher collaboration ratings than quartets. Subsequent studies discontinued size comparisons to focus deeply on optimizing interaction quality within the dyadic structure.
Device and Interface Policy	Shared Tablets: Students worked Face-to-Face (F-F) sharing iPad devices.	Individual Smartphones (BYOD): 1:1 device ratio; partners used own phones but had interdependent roles.	Individual Smartphones (BYOD): 1:1 device ratio; partners used own phones with complementary traits.	The shift to smartphones increased ecological validity (BYOD). Furthermore, moving from a shared screen (Study I) to a 1:1 ratio (Study II/III) was intended to distribute the cognitive burden. By providing each partner with a private view of their specific variables, the design aimed to reduce the extraneous load associated with managing physical access to a single shared device, thereby theoretically optimizing the "collaborative cognitive load".
Reflection Support (Metacognitive Gear)	Implicit / Minimal: No in-task prompts; brief 5–7 min teacher debrief only.	Structured Scaffolding: Embedded worksheet prompts and extended (17 min) teacher-led debrief.	Mature RRL Protocol: Domain-specific questionnaires coded via the *Remember-Recall-Learning* protocol.	Study I revealed that interaction alone did not guarantee deep inquiry. Study II added structure to support Socially Shared Regulation (SSRL). Study III formalized this into the RRL protocol to rigorously measure metacognitive growth.
Role Asymmetry (Social Gear)	Split Control: Student A (Season) vs. Student B (Lamp Intensity).	Split Function: Student A (Voltage/Switch) vs. Student B (Resistance).	Split Traits: Student A (Black Fur genes) vs. Student B (White Fur genes).	The core mechanic of "information gaps" was retained but refined. Later studies increased the complexity of interdependence to force negotiation, addressing the "social loafing" risks observed in larger groups in Study I.
Assessment Focus	Basic Collaboration: 4-item scale (Hinyard et al.) and Rubric-scored tasks.	Multidimensional CPS: ATC21S Framework (10 items) and Interdependence scale.	Triangulated CPS and RRL: ATC21S Framework and RRL Coding of reflections.	Measurement instruments evolved from simple team ratings to validated frameworks (ATC21S) to capture specific dimensions like *social regulation* and *perspective-taking* required by the TEAC framework.

Detailed descriptions of all instruments, scoring procedures, and reliability indicators associated with each learning dimension are presented in Sections 3.5.1–3.5.4 and synthesized in Table 1. To make the iterative refinement of the TEAC framework explicit, Table 2 summarizes the cumulative design decisions that emerged across the three DBR cycles. It functions as a transparent *version history* of the intervention, outlining how key design features evolved and documenting the empirical and theoretical rationales that guided each modification prior to the presentation of the individual studies.

The design-based research framework thus provided the structural foundation for the methodological choices detailed in this chapter. By situating the inquiry within this iterative model, the research systematically investigated technology-enhanced asymmetric collaboration as a dynamic pedagogical approach, allowing for the continuous refinement of the TEAC framework within the complexity of authentic classroom settings

3.2. Sampling and Design Rationale

The sampling and design decisions across Studies I–III were guided by the objectives of the design-based research approach and by the conceptual structure of the TEAC framework. Rather than aiming for representativeness or statistical generalization, the studies were designed to support iterative refinement of a pedagogical approach within authentic classroom contexts. Consequently, participant selection, group configurations, and instructional designs were shaped by curricular relevance, feasibility in school settings, and alignment with the learning dimensions under investigation.

All three studies were conducted in lower secondary school science classrooms, corresponding to the target context of the TEAC framework. The participating classes were selected through convenience sampling in collaboration with schools willing to integrate technology-enhanced inquiry activities into regular instruction. Each design-based research cycle involved an independent student cohort, reflecting differences in grade level, school context, and classroom availability. Variations in sample size across the three studies are therefore intentional and design-driven, consistent with the logic of design-based research in authentic educational settings. Coherence across studies is established through shared design principles, aligned instruments, and a common analytic framework, rather than through identical participant groups. The researcher acted strictly as an observer during all interventions; the regular classroom teachers delivered the lessons using the provided materials.

Sampling decisions were closely linked to the learning dimensions addressed in each research question. In Study I, which focused on inquiry performance and collaborative interaction, group size was treated as a key design parameter. Accordingly, dyads and four-person groups were formed to examine how different group configurations influenced inquiry outcomes and perceived collaboration. In Study II, the sampling strategy prioritized small-group settings that allowed

for structured role asymmetry and close examination of collaborative problem-solving processes. Study III retained small-group configurations while introducing reflective scaffolding, reflecting the increasing emphasis on metacognitive regulation and reflective evaluation of collaboration.

Across studies, variation in grade level was intentional and aligned with the progressive refinement of the TEAC framework. Study I involved younger students working with relatively concrete scientific concepts, enabling initial exploration of asymmetric collaboration and inquiry tasks. Study II introduced more complex problem-solving demands, while Study III engaged older students with abstract scientific content, creating conditions in which regulation and reflection became particularly salient learning dimensions. This progression supported the examination of TEAC principles across different developmental stages and content domains.

The selection of simulation topics across the three studies was guided by both conceptual and instructional considerations. Photosynthesis, electricity, and genetics involve abstract and largely non-observable scientific phenomena that are well documented as challenging for students' conceptual understanding. In the context of photosynthesis, learners frequently hold persistent non-normative conceptions related to energy transformation processes (Pei et al., 2020). Genetics requires reasoning across invisible and multi-level constructs, such as alleles and inheritance mechanisms, which places substantial demands on students' ability to coordinate representations and explanations (Sui et al., 2022). Similarly, in electricity, students often struggle to articulate, regulate, and make explicit their understanding of non-observable relations such as current, voltage, and resistance during inquiry activities (Popov et al., 2018).

From an instructional perspective, inquiry learning in such abstract domains is particularly vulnerable to cognitive overload when insufficiently guided. CLT explains that unguided problem solving can place excessive demands on working memory, thereby hindering schema acquisition and conceptual learning (Kalyuga et al., 2003; Sweller, 1988, 2022). Meta-analytical evidence further indicates that IBL yields positive learning outcomes primarily when supported by explicit structural guidance, whereas unassisted discovery approaches often lead to procedural rather than conceptual learning gains (de Jong et al., 2023; Lazonder & Harmsen, 2016). Taken together, these findings provide a strong rationale for selecting photosynthesis, electricity, and genetics as empirical contexts for examining and refining the structurally guided, technology-enhanced inquiry approach implemented through the TEAC framework.

Design decisions regarding tasks, tools, and data sources were likewise informed by the research questions and learning dimensions summarized in Table 1. Inquiry tasks, worksheets, questionnaires, reflections, and observations were selected to capture both learning outcomes and learning processes. Analytic approaches, including rubric-based scoring, statistical comparisons, qualitative content analysis, and triangulation across data sources, were chosen to balance methodological rigour with sensitivity to classroom complexity.

3.3. Study I

Study I constituted the first design-based research cycle and served as an initial empirical implementation of technology-enhanced asymmetric collaboration in a formal school science context. The methodological purpose of this study was to examine how group size influences inquiry performance and collaborative dynamics when students engage with a shared digital simulation under asymmetric conditions. In line with the TEAC framework, Study I primarily targeted learning dimensions related to knowledge construction and collaborative interaction. The alignment between Research Question 1, the targeted learning dimensions, data sources, and analytic approaches in Study I is summarized in Table 1.

The study was conducted in a public school in Tartu, Estonia, and involved fifth-grade and sixth-grade students participating in a photosynthesis learning unit supported by a digital laboratory environment. The participant sample consisted of 58 fifth-grade students with a mean age of 11.3 years and 74 sixth-grade students with a mean age of 12.4 years. Students worked either in dyads or in four-person groups, allowing for systematic comparison of group size configurations within the same instructional design.

In the Photosynthesis Digital Lab, asymmetric collaboration was operationalized through complementary role distribution. One student controlled seasonal conditions (Summer/Winter), while the other adjusted lamp intensity (Off/Weak/Strong), creating an information gap that required verbal coordination. Although both students observed the same real-time simulation output (e.g. bubble production), neither could independently manipulate all task-relevant variables, thereby enforcing interdependence during inquiry. Procedural constraints further required students to articulate their observations and reasoning, ensuring that task progression depended on shared interpretation rather than individual action. An overview of the Photosynthesis Digital Lab used in Study I is presented in Figure 3.

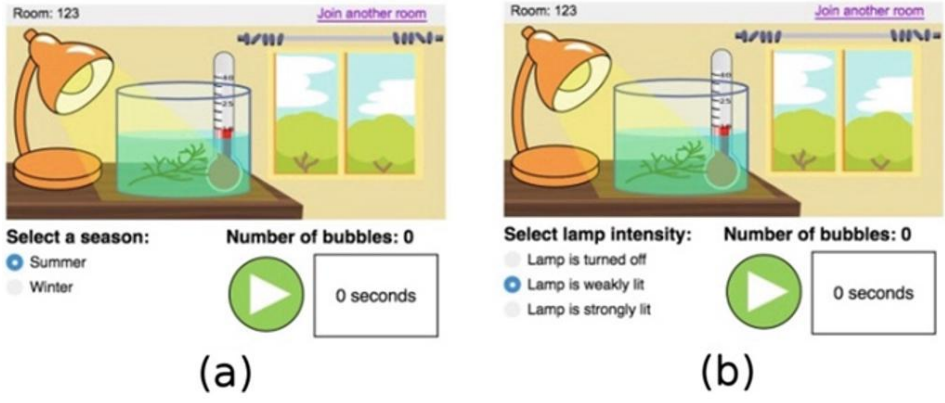

Figure 3. *Photosynthesis Digital Lab (Study I)*

Data collection in Study I was designed to capture both inquiry outcomes and students' perceptions of collaboration. Inquiry performance was assessed through open-ended tasks completed immediately after the learning activity, requiring students to apply their understanding of photosynthesis to novel situations involving changes in light intensity and seasonal conditions. Perceived collaboration quality was measured using a short questionnaire focusing on information sharing, team support, and collective learning. In addition, students' written responses were examined qualitatively to identify inquiry-related and collaboration-related difficulties that emerged during task completion.

From a design-based research perspective, Study I provided an initial empirical basis for evaluating the feasibility of asymmetric collaborative simulations in classroom settings and for identifying design constraints related to group size.

The findings highlighted challenges associated with coordination, shared regulation, and uneven participation, particularly in larger groups. These insights informed subsequent refinements in group configuration, role differentiation, and measurement strategies implemented in Studies II and III.

3.4. Study II

Study II constituted the second design-based research cycle and built directly on methodological insights gained in Study I. While the first cycle examined the effects of group size under asymmetric conditions, Study II introduced structured role asymmetry as a deliberate design feature. The methodological purpose of this study was to examine how clearly differentiated roles influence students' ability to co-construct knowledge and engage in CPS during technology-enhanced inquiry activities. In terms of the TEAC framework, Study II placed particular emphasis on learning dimensions related to collaborative interaction and inquiry knowledge, while retaining a focus on knowledge construction. The alignment between Research Question 2 and 3, the targeted learning dimensions, data sources, and analytic approaches in Study II is summarized in Table 1.

The instructional design of Study II centred on inquiry tasks related to basic electrical circuits, supported by the Electricity Digital Lab. In contrast to Study I, students were assigned explicit and complementary roles that distributed access to information, control over simulation elements, and responsibility for specific inquiry actions. This structured role asymmetry was intended to increase interdependence, make collaborative processes more visible, and foreground participation, perspective-taking, and social regulation during problem solving.

In the Electricity Digital Lab, asymmetric collaboration was operationalized through the distribution of circuit control variables across dyads. One student controlled power-related elements, such as voltage selection and switch activation, while the other manipulated resistance values and circuit configurations. This division created a functional information gap, as neither student had full control over the circuit behaviour. Although both partners observed the same real-time circuit visualization and system feedback, successful task completion required

continuous verbal coordination, hypothesis testing, and joint interpretation of system responses. Procedural constraints further ensured that students relied on communicated observations rather than independent manipulation of all variables. An overview of the Electricity Digital Lab is presented in Figure 4.

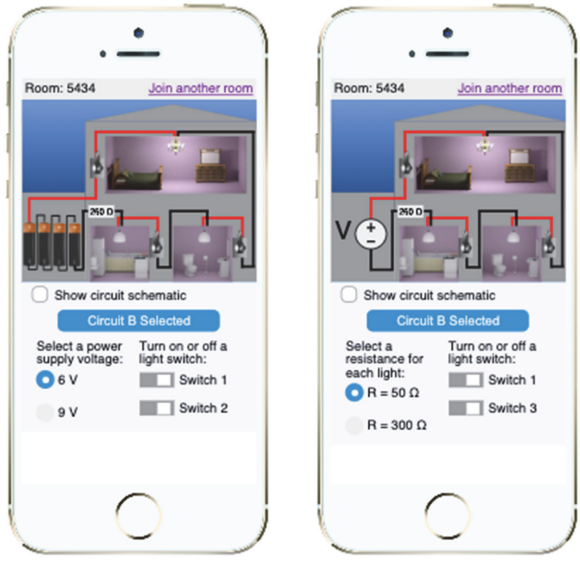

Figure 4. *Electricity Digital Lab (Study II)*

Data collection in Study II was expanded to capture both learning outcomes and collaborative processes in greater detail. Subject knowledge and inquiry knowledge were assessed through open-ended worksheet tasks embedded within the learning activity, requiring students to reason about circuit functionality and identify independent and dependent variables. Collaborative problem-solving processes were examined using a questionnaire based on established CPS frameworks, focusing on participation, perspective-taking, social regulation, and interdependence. In addition, structured reflection prompts were embedded in the worksheets to elicit students' evaluations of their strategies, communication, and task-related challenges. Classroom observations conducted by the researcher provided further contextual insight into interaction patterns and the enactment of assigned roles.

From a design-based research perspective, Study II functioned as a critical refinement cycle in which the pedagogical affordances and limitations of structured role asymmetry were systematically examined. Although role differentiation enhanced interdependence and made collaborative processes more explicit, the findings also revealed variation in students' ability to regulate inquiry processes and to reflect meaningfully on their collaboration. These insights informed the subsequent integration of more systematic reflective scaffolding in Study III, where metacognitive regulation became a central focus of the TEAC framework.

3.5. Study III

Study III constituted the third design-based research cycle and focused on the refinement and consolidation of the TEAC framework through the systematic integration of reflective scaffolding. Building on the findings of Studies I and II, which highlighted challenges related to coordination, regulation, and students' ability to evaluate their collaborative processes, Study III explicitly foregrounded metacognitive regulation as a central learning dimension. The methodological purpose of this study was to examine how structured reflection supports students' regulation of collaborative inquiry and their understanding of complex scientific concepts. The alignment between Research Question 2 and 3, the targeted learning dimensions, data sources, and analytic approaches in Study III is summarized in Table 2.

The study was conducted in a Grade 9 science classroom using a genetics learning unit supported by a digital laboratory environment. The participant sample consisted of 43 ninth-grade students with a mean age of 15.7 years ($SD = 0.34$). Students worked in pairs and small triads, reflecting both pedagogical considerations and classroom constraints. The instructional context involved abstract genetic concepts, including inheritance patterns and variable relationships, which provided a suitable setting for examining regulatory and reflective learning processes.

The instructional design of Study III retained the structured role asymmetry introduced in Study II, ensuring differentiated access to information and simulation controls. In the Genetics Digital Lab, asymmetric collaboration was operationalized through complementary control over genetically relevant task elements. Learners were assigned differentiated roles that distributed access to specific trait-related information and simulation actions so that neither partner could independently generate or interpret the complete inheritance outcome. Both learners observed the same emergent offspring patterns and visual outputs, but successful task completion required them to coordinate interpretations, compare observations, and jointly reason about genotype–phenotype relationships. In addition, systematic reflection prompts were embedded at key stages of the inquiry process. These prompts required students to recall their initial reasoning, evaluate the correctness of their conclusions, and articulate what they had learned through collaboration. The design of the reflection prompts was informed by insights from Study II and aimed to support regulation of both inquiry processes and collaborative interaction rather than procedural task completion. An overview of the two mobile simulation versions (A and B) of the Genetics Digital Lab used in Study III is presented in Figure 5.

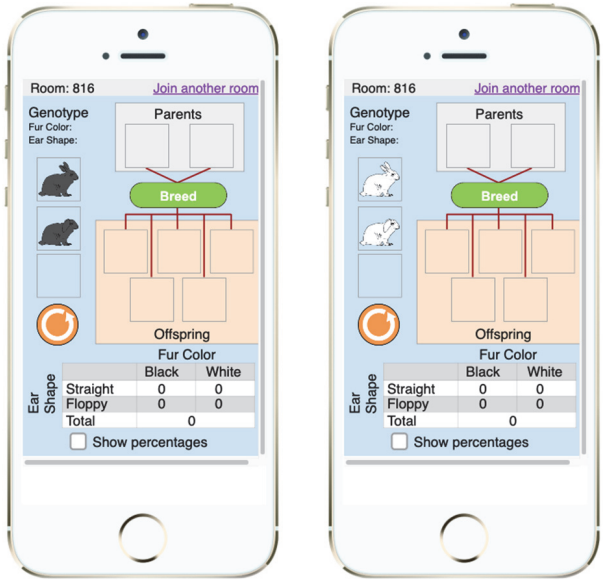

Figure 5. *Genetics Digital Lab (Study III)*

Data collection in Study III was designed to capture learning outcomes, collaborative processes, and metacognitive regulation in an integrated manner. Subject knowledge and inquiry knowledge were assessed through open-ended worksheet tasks addressing basic inheritance concepts, abstract genetic problems, and reasoning about independent and dependent variables. Students' perceptions of CPS were examined using the same CPS questionnaire employed in Study II, allowing for continuity and comparison across studies. Reflective responses were analysed using a structured coding approach that distinguished between recall of reasoning, evaluation of correctness, and evidence of conceptual learning. Classroom observations and teacher-facilitated discussions provided additional contextual information regarding interaction patterns and engagement with reflective scaffolds.

From a design-based research perspective, Study III functioned as a synthesis and refinement cycle in which earlier design elements were stabilized and extended. The integration of structured reflection enabled a more explicit examination of regulatory processes and their relationship to inquiry outcomes and perceived collaboration benefits. Together with Studies I and II, Study III contributed to the empirical grounding of the TEAC framework and demonstrated how technology-enhanced asymmetric collaboration can be systematically supported through guided reflection in authentic classroom settings.

3.6. Analytic Procedures and Quality Assurance

This section specifies the analytic procedures applied across Studies I–III and outlines the strategies used to ensure methodological quality, reliability, and trustworthiness. Consistent with the design-based research approach, analysis addressed both learning outcomes and learning processes, with particular attention to how these evolved across iterative research cycles. Analytic decisions were explicitly aligned with the research questions and learning dimensions summarized in Table 1 and were progressively refined in parallel with the development of the TEAC framework.

Quantitative Analytic Procedures were used to examine patterns in inquiry performance, subject knowledge, inquiry knowledge, and selected dimensions of CPS. Open-ended inquiry and knowledge tasks were evaluated using study-specific structured rubrics that differentiated between levels of conceptual accuracy and reasoning quality. Where multiple raters were involved, interrater reliability was calculated to ensure scoring consistency.

Given the sample sizes and non-normal distribution of the data, non-parametric statistical methods were employed throughout. Group-level comparisons, including contrasts between group configurations and simulation versions, were conducted using Mann–Whitney U tests. Questionnaire data related to collaborative problem-solving dimensions were summarized using descriptive statistics. In Study III, Spearman correlation analyses were applied to examine associations between students' perceived collaboration benefits and combined subject and inquiry knowledge scores.

The internal consistency of questionnaire scales was assessed using Cronbach's alpha. In cases where reliability coefficients were low, findings were interpreted with caution and considered in conjunction with qualitative evidence, in line with mixed-methods recommendations for research conducted in authentic classroom settings.

Qualitative Analytic Procedures were employed to capture aspects of students' reasoning, interaction, and reflective regulation that could not be adequately represented through quantitative measures alone. Written responses to open-ended tasks, reflection prompts, and classroom observation notes were analysed using qualitative content analysis. Coding schemes were informed by the theoretical framework and iteratively refined through close engagement with the data.

In Study I, qualitative analysis focused on identifying inquiry-related and collaboration-related difficulties evident in students' task responses. In Studies II and III, reflective data were analysed to examine how students evaluated their inquiry processes, collaborative dynamics, and learning outcomes. In Study III, reflective responses were further analysed using a structured coding approach that distinguished between recall of reasoning, evaluation of correctness, and evidence of conceptual learning, enabling systematic examination of metacognitive regulation.

Classroom observations and teacher-facilitated discussions were used to contextualize students' written responses and to support interpretation of questionnaire findings. These data sources provided insight into role enactment, interactional patterns during inquiry activities, and students' engagement with reflective scaffolds.

Triangulation and Trustworthiness. Across all studies, methodological triangulation was employed to enhance interpretive robustness. Quantitative and qualitative data sources were analysed in parallel and integrated during interpretation to examine convergence and divergence across measures. Rather than privileging a single data source, the analytic strategy sought to represent the multifaceted nature of technology-enhanced collaborative inquiry by combining outcome-oriented and process-oriented evidence.

Design-based research principles further supported trustworthiness by enabling iterative refinement of analytic focus and instrumentation. Insights from earlier studies informed both design modifications and analytic strategies in subsequent cycles, supporting cumulative knowledge building rather than isolated findings. Transparency in reporting analytic procedures, reliability indicators, and methodological limitations was prioritized to allow readers to evaluate the rigour and scope of the analyses.

The analytic procedures across Studies I–III were thus systematically aligned with the learning dimensions of the TEAC framework, ensuring they remained responsive to the constraints and affordances of authentic classroom contexts. By integrating quantitative and qualitative analyses with explicit attention to reliability and triangulation, the research design supported a rigorous and context-sensitive examination of technology-enhanced asymmetric collaboration.

3.7. Validity, Reliability, and Methodological Quality

Across the three design-based research cycles, the development, adaptation, and application of research instruments were conducted through a collaborative research process. While the author held primary responsibility for the overall research design, task construction, and analytic framework, the co-authors of the individual studies contributed to instrument refinement, the validation of scoring procedures, and the interpretation of coded data. In particular, the development of scoring rubrics, reflection coding schemes, and questionnaire adaptations was discussed iteratively within the research team to ensure conceptual alignment, clarity of criteria, and consistency of interpretation across raters.

Coding procedures for open-ended responses and reflective data were refined through collaborative review and joint examination of sample responses. Where applicable, interrater agreement was calculated to support consistency in scoring. In cases where formal reliability coefficients were not reported for all qualitative dimensions, coding decisions were strengthened through repeated comparison of coded data, consensus-oriented discussions, and alignment with theoretically defined indicators. This approach reflects qualitative quality criteria that

emphasize transparency, coherence, and analytic rigour rather than sole reliance on statistical reliability indices.

Methodological quality was addressed not by treating validity and reliability as isolated psychometric properties of individual instruments, but through systematic alignment between theoretical constructs, task design, data sources, and analytic procedures. The use of multiple complementary instruments, including rubric-scored inquiry tasks, self-report questionnaires, structured reflection protocols, and classroom observations, enabled methodological triangulation across both learning outcomes and learning processes. This layered approach reduced the risk of single-source bias and supported robust interpretation within the constraints of authentic classroom research.

Overall, instrument development and data analysis were embedded within an iterative and collaborative research process that combined theoretical grounding, empirical refinement, and peer validation. This process-oriented approach to methodological quality is consistent with design-based research principles and supports the credibility and trustworthiness of findings derived from complex, context-sensitive learning environments.

3.8. Cross-Study Synthesis and Iterative Refinement of the TEAC Framework

The Technology-Enhanced Asymmetric Collaboration (TEAC) framework was iteratively developed and examined through three consecutive design-based research cycles conducted in authentic Estonian classroom settings, involving students from Grade 5 to Grade 9. While each study addressed a distinct methodological focus, together they formed a cumulative research trajectory aligned with the three overarching research questions introduced in Section 1.2. An overview of the studies, including their focal learning dimensions, data sources, and analytic approaches, is provided in Table 1 at the beginning of this chapter.

Across all cycles, the TEAC framework operationalized three interrelated learning processes: knowledge construction, collaborative interaction, and regulation through reflection. These processes, conceptualized as the learning gears of TEAC, guided the design of role-differentiated simulations, inquiry tasks, assessment instruments, and reflective scaffolds. Rather than treating the studies as isolated implementations, the design-based research approach enabled systematic refinement of the framework in response to empirical findings and contextual constraints.

Study I established the foundational feasibility of implementing role-asymmetric simulations in lower secondary science classrooms. The focus on group size revealed that dyadic configurations supported more favourable collaborative conditions than larger groups, although limitations in process-level data and the absence of structured reflection highlighted the need for more explicit scaffolding and richer analytic tools. These insights informed subsequent design decisions and measurement strategies.

Study II addressed these limitations by introducing structured role asymmetry, expanded collaborative problem-solving measures aligned with the ATC21S framework, and embedded reflection prompts supported by teacher-facilitated debriefing. While role differentiation strengthened interdependence and perspective-taking, the study also revealed that students' conceptual understanding of variable relationships and their regulation of inquiry processes required further support. Methodologically, this cycle underscored the importance of integrating reflection more systematically and strengthening triangulation across data sources.

Study III represented the most refined iteration of the TEAC framework, integrating a multi-dimensional reflection protocol based on the Remember–Recall–Learning (RRL) coding scheme. This design enabled systematic examination of metacognitive regulation alongside inquiry performance and collaborative problem-solving measures. The integration of rubric-scored tasks, CPS questionnaires, coded reflections, and classroom observations provided the most comprehensive insight into how students regulate their learning within technology-enhanced asymmetric collaboration.

Across all three studies, methodological triangulation was a central design principle. Knowledge construction was assessed using open-ended tasks scored with progressively refined rubrics, collaborative interaction was examined through developmentally appropriate Likert-scale instruments grounded in established CPS frameworks, and regulation through reflection was captured through structured prompts, discussions, and theory-informed coding schemes. Quantitative analyses were complemented by qualitative interpretation to capture both learning outcomes and learning processes.

Importantly, the iterative refinement of TEAC also involved deliberate design decisions regarding what not to include. Fixed digital scripting tools and real-time teacher dashboards were considered but ultimately excluded to preserve ecological validity and avoid excessive cognitive load. These decisions reflect a commitment to balancing structural guidance with pedagogical flexibility in authentic classroom settings.

3.9. Ethical Considerations

This research adhered to established ethical standards for educational research involving minors and was conducted in accordance with institutional guidelines and the Estonian Code of Conduct for Research Integrity (2017). Prior to data collection, approval to conduct the studies was obtained from the administrations and teachers of all participating schools. Students were informed about the purpose of the research, the nature of the learning activities, and the types of data being collected. Participation in all research components, including questionnaires and reflective tasks, was voluntary, and students were informed of their right to withdraw at any stage without academic consequences.

All learning activities were aligned with the national curriculum and implemented as part of regular science instruction. No experimental conditions involved withholding instruction or exposing students to learning tasks beyond their expected curricular level. The technology-enhanced inquiry activities and collaborative tasks were designed to support learning rather than to evaluate students for grading purposes, thereby minimizing potential pressure or harm.

To ensure confidentiality and data protection, all student data were anonymized immediately upon collection. Personal identifiers were replaced with alphanumeric codes, and no personally identifiable information was included in analytical datasets. Data were stored securely in accordance with data protection regulations, with access restricted to the researcher. Video or audio recordings were not used in the final analysis; instead, analyses relied on written artifacts, system logs, anonymized worksheets, reflections, and field notes. The use of digital simulations did not involve the collection of sensitive personal data.

Classroom observations focused on interaction patterns and learning processes rather than individual behaviour. Particular care was taken when analysing students' self-evaluations and reflections to avoid deficit-oriented interpretations, especially given developmental differences across grade levels. From a design-based research perspective, ethical responsibility also involved responsiveness to classroom realities. Iterative refinements to the instructional design were made with the primary aim of improving learning conditions rather than optimizing research outcomes alone, ensuring that the pedagogical interventions remained educationally meaningful, proportionate, and respectful of participants' time and learning needs.

3.10. Use of Generative Artificial Intelligence and Digital Research Tools in the Preparation of the Thesis

In the preparation of this doctoral thesis, the generative artificial intelligence tool ChatGPT (OpenAI, n.d.) was employed in a limited and clearly defined capacity as a language and structural support resource. Its application was confined to tasks that did not involve the creation of original research content, empirical findings, or conceptual arguments. Specifically, ChatGPT was utilized to refine the clarity and coherence of language, to improve sentence structure, and to ensure consistency in the use of academic terminology.

The tool was also employed in the rephrasing of author-generated text to avoid unnecessary repetition and to enhance stylistic uniformity across chapters. On selected occasions, it was used to produce preliminary translations between Estonian and English, all of which were subsequently reviewed, edited, and verified by the author to ensure terminological precision and contextual accuracy. Furthermore, ChatGPT was consulted for suggestions related to the logical flow and organization of the thesis text, particularly in sections describing the methodology and presenting the results.

In addition to ChatGPT, the digital research tool Litmaps (https://app.litmaps.com) was used to support the literature review process. Litmaps facilitated the identification of relevant academic publications through citation network visualization, enabling the detection of key sources, thematic clusters, and research gaps. This tool was particularly useful in tracing the development of theoretical concepts over time and in verifying the completeness of the reference base. All literature identified via Litmaps was subsequently assessed by the author for relevance, credibility, and quality before being integrated into the thesis.

At all stages, the input provided to both ChatGPT and Litmaps originated from the author, and the output generated by these tools was subject to thorough critical review, editing, and adaptation before inclusion in the final manuscript. The intellectual content, interpretations, and conclusions presented in this thesis are solely those of the author. The role of ChatGPT was restricted to supporting the linguistic and structural quality of the written work, while Litmaps served as a supplementary aid in literature mapping and organization. Both tools were employed in accordance with the principles of transparency, critical engagement, and ethical use of digital and artificial intelligence resources in academic writing.

4. FINDINGS I: Knowledge Construction (Addressing RQ2 and informed by RQ1)

This chapter examines how the TEAC framework supported students' construction of scientific knowledge across three design-based research (DBR) studies. The findings are presented across three results chapters, organized according to the core learning processes of the TEAC framework: knowledge construction (Chapter 4), collaborative interaction (Chapter 5), and metacognitive regulation (Chapter 6).

To support clarity, the alignment between the research questions and the results chapters is made explicit. Research Question 1 (group size) is addressed through inquiry outcomes in Chapter 4 and collaboration outcomes in Chapter 5. Research Question 2 (role asymmetry) is examined through its effects on knowledge construction in Chapter 4 and collaborative interaction patterns in Chapter 5. Research Question 3 (reflective practices) is addressed in Chapter 6, which focuses on metacognitive regulation.

To further clarify the analytical structure, the independent variables across these studies were group configuration (Study I) and structured role asymmetry (Studies II and III). The dependent variables examined in this chapter are learning outcomes, specifically subject knowledge (K1/K2) and inquiry knowledge (K3/UT). This distinction makes explicit how the study design variables are analytically linked to measured learning outcomes and ensures alignment between the research questions, theoretical framework, and the presentation of results.

Chapter 4 focuses specifically on these learning outcomes. Section 4.1 presents subject-knowledge outcomes (K1/K2), comparing dyadic and quartet groupings on open-response tasks following photosynthesis, electricity, and genetics simulations. Section 4.2 examines inquiry-knowledge outcomes (K3/UT), highlighting persistent challenges in applying conceptual understanding to experimental tasks, particularly in relation to variable identification. Section 4.3 analyses task-performance metrics and error patterns, categorizing syntax, collaboration, and inquiry errors to reveal common misconceptions and coordination breakdowns under asymmetric conditions. Section 4.4 synthesizes these findings by illustrating how TEAC's core design priorities, structured role distribution, contextualized teacher facilitation, and scaffolded reflection interacted to support deeper cognitive engagement. Qualitative analyses demonstrate improvements in variable reasoning and reveal associations between perceived collaboration benefits and combined knowledge scores, while student reflections and illustrative quotations underscore the pedagogical supports required to translate structured interdependence into robust conceptual learning.

While Table 2 documents the evolution of the TEAC design across DBR cycles and Table 1 outlines the methodological alignment, Table 3 provides a comparative summary of the key empirical findings and student learning outcomes across the three studies.

Table 3. *Cross-Study Overview of Design, Participants, and Key Findings*

Feature	Study I (Rannastu et al., 2019)	Study II (Rannastu-Avalos et al., 2023)	Study III (Rannastu-Avalos et al., 2025)
Key Findings (Collaboration)	No significant difference by group size (Grade 5); In Grade 6, dyads achieved higher raw scores for inquiry and made fewer errors, though these differences in inquiry performance were not statistically significant across group sizes, and error counts were not statistically tested for significance; dyads also reported higher collaboration ratings.	Teacher-led debrief critical for effective collaboration; High ratings: perspective-taking, social regulation; Interdependence rated lowest despite design; Low-scoring groups emphasized social interaction over learning outcomes	High student engagement (93% effort, 81% active participation); Strong social regulation (95% acknowledging peer differences); perspective-taking high (86% clarifying misunderstandings); Moderate positive correlation between perceived collaboration benefits and learning performance ($r = .42$, $p < .05$); Interdependence perception varied (42–60%); collaboration sometimes perceived as slowing progress
Key Findings (Inquiry / Subject Knowledge)	Inquiry scores low overall (28% Grade 5; 40% Grade 6); No significant difference by group size; Seasonal effect tasks more difficult (more errors)	Identifying independent/dependent variables was main difficulty; 55% correctly identified variables; Teacher-led discussions essential; Experimentation and communication critical	K1 (basic genetics): 81% high-level performance; K2 (complex genetics): 42% high-level, required deeper reasoning; K3 (variables identification): 23% high-level, 47% average; Visible learning during reflection: K1 (77%), K2 (42%), K3 (51%); Strong theoretical knowledge, inconsistent inquiry application
Limitations / Future Directions	Inquiry tasks challenging; further guidance and practice needed; Recommend longitudinal research with larger samples; Highlight teacher role in feedback and scaffolding	Single-session design limits generalizability; Future iterations should include diverse science topics, clearer visuals and examples; Continuous reflection practice needed; clarify interdependence logic	Single-lesson, no control group, limits causality and generalizability; Self-report CPS may introduce bias; low internal consistency (perspective-taking α=.141, social regulation α=–.101, interdependence α=.359); Future studies: longitudinal designs, control groups, multi-method assessments (e.g. observations, peer/teacher ratings); Improve task clarity, interface responsiveness, instructional prompts emphasizing role dependence

4.1. Subject-Knowledge Outcomes (K1/K2) Across Studies

The TEAC framework compels sustained verbal and digital coordination by assigning each partner control over distinct simulation variables, thereby creating structural positive interdependence where neither student can resolve the task alone (Article 1; Article 2; Article 3). Rather than analysing micro-level sensory data, TEAC captures the efficacy of these compelled interactions by triangulating subject-knowledge outcomes measured immediately after each simulation with student reflections on their collaborative process.

Table 4. *The Knowledge Construction Outcomes Across Studies*

Study	Task Domain	Key Finding / Score
Study I (Gr 5)	Inquiry (Tasks A+B)	20% correct (Quartets) vs. 28% correct (Dyads)
Study I (Gr 6)	Inquiry (Tasks A+B)	40% correct (Quartets) vs. 61% correct (Dyads)
Study II (Gr 7)	Subject (Circuits)	11 groups fully correct; 10 groups incorrect
Study III (Gr 9)	K1 (Basic Knowledge)	81% High level; 12% Average; 7% Low
Study III (Gr 9)	K2 (Conceptual)	42% High level; 16% Average; 19% Low
Study III (Gr 9)	K3 (Inquiry/CVS)	23% High level; 47% Average; 21% Low

As shown in Table 4, knowledge construction outcomes across all three studies can be compared systematically, allowing cross-study comparison of subject knowledge and inquiry performance. Presenting these results in tabular form clarifies patterns that were previously embedded in narrative descriptions, particularly the consistent advantage of dyads over quartets in inquiry tasks and the decline in performance as tasks shifted from basic subject knowledge (K1) towards conceptual (K2) and inquiry-based reasoning (K3). This synthesis supports the analytical distinction between content mastery and inquiry skill application developed in the subsequent analysis.

Study I: Photosynthesis Digital Lab (Grades 5–6). In the first study, fifth- and sixth-grade students worked in two- or four-person teams on iPads, with one partner adjusting lamp intensity and the other selecting season to explore photosynthesis (Article 1). Subject-knowledge was assessed via two open-response tasks, each worth two points, administered immediately after the activity. Four-person teams of fifth graders scored 20% correct, while sixth-grade four-person teams scored 38.25% (rounded to 40%) on combined Tasks A and B. When groups were reorganized into dyads, sixth-grade pairs improved relative to quartets, with the same pattern observed among fifth graders, as shown in Table 4. Although statistical tests did not confirm significant differences in accuracy across group sizes, the observed pattern suggests that dyadic configurations supported more focused collaboration and reduced coordination demands compared to larger groups. At the same time, overall inquiry scores remained modest, indicating that while the asymmetric design successfully compelled interaction,

additional instructional support was needed to help students transform collaboration into deeper conceptual understanding. Observed collaboration errors, such as responding to a partner's prompt as if it were one's own task, further highlighted that sharing and integrating unique information remained a developing skill.

Study II: Electricity Digital Lab (Grade 7). The second study engaged forty-four seventh-grade students in pairs (and three triplets) on the Electricity Digital Lab via smartphones (Article 2). Subject-knowledge outcomes were recorded by evaluating whether each group correctly constructed a given electrical circuit. Of twenty-two teams, eleven achieved fully correct circuits, ten produced incorrect solutions, and one produced a partially correct solution due to mismatched partner responses. Inquiry knowledge tasks, distinguishing independent and dependent variables, proved difficult: 55% of students in Version A identified independent variables correctly, whereas Version B participants continued to confuse variables despite a teacher-led debrief. One learner commented, "My answer was wrong because neither of us really understood what was a dependent and what was an independent variable". These outcomes demonstrate that, although the asymmetric design successfully compelled interdependent interaction, conceptual grasp of variable relationships required more targeted scaffolding, particularly through systematic guided reflection and discussion.

Study III: Genetics Digital Lab (Grade 9). The third study examined forty-three ninth-grade students collaborating via a smartphone-based genetics simulation (Article 3). On a basic inheritance question (K1), 81% of students performed at a high level, 12% at an average level, and 7% at a low level. On a more abstract genetics problem (K2), only 42% achieved high performance, 16% average, 19% low, and 23% did not respond. High-level responses correctly identified parental genotypes required for specific trait probabilities (for example, "One rabbit must be Bb and the other bb to give a 50% chance of floppy or straight ears"), whereas low-level answers lacked principled genetic reasoning. The high nonresponse rate underscores the difficulty of transferring basic conceptual knowledge to more complex reasoning tasks, even when collaboration is mandated by the simulation design.

Synthesis. Across all three studies, TEAC's asymmetric simulations reliably enforced interdependent verbal and digital coordination (The Social Gear) yet converting that interaction into deep conceptual understanding (The Cognitive Gear) remained challenging. Dyadic configurations tended to produce higher raw scores on simpler tasks, but none of the observed gains in Study I reached statistical significance, and significant conceptual hurdles persisted in identifying variables (Studies II and III) and in abstract reasoning (Study III). These findings suggest a hierarchy within the TEAC framework: while the asymmetric design is effective at compelling collaboration, this interaction does not automatically result in knowledge gains. Additional metacognitive scaffolds, such as specifically targeted practice in variable classification and structured reflection, are necessary to bridge the gap between social interdependence and scientific conceptual knowledge.

4.2. Inquiry-Knowledge Outcomes (K3/UT) Across Studies

Inquiry-knowledge outcomes evaluate students' capacity to apply their conceptual understanding to experimental tasks under asymmetric collaborative conditions. Although TEAC's design enforces sustained verbal and digital coordination, all three studies reveal that interdependent interaction alone does not guarantee robust inquiry skills, particularly control-of-variables strategy (CVS) and accurate variable identification.

Study I: Photosynthesis Simulation (Grades 5–6). In the Photosynthesis Digital Lab, fifth- and sixth-grade teams worked in dyads or quartets using iPads, with one partner adjusting lamp intensity and the other selecting season (Article 1). Overall inquiry accuracy was low: 28% for fifth graders and 40% for sixth graders. Although dyads sometimes outperformed quartets, these differences were not statistically significant in either grade. Error analysis identified frequent "Inquiry" errors, students changed more than one variable at once or failed to conduct systematic trials, producing misinterpretations such as "Slowly in winter but fast in summer". Task B (season) proved more error-prone than Task A (light intensity), suggesting reliance on prior knowledge when experiments lacked clear structure. These findings indicate that simply requiring students to coordinate controls does not foster deeper experimental reasoning or a systematic CVS approach.

Connection to Variable-Definition Slide. The lesson materials included a slide titled "Conducting Experiments," which defined independent and dependent variables: the independent variable is what you change, and the dependent variable is what you measure. Both versions of the worksheet reinforced this definition. Despite this clear instruction and discussion, students in Studies II and III still struggled to apply these concepts in practice, indicating that passive presentation, even when supported by guided review, does not guarantee lasting understanding.

Study II: Electricity Simulation (Grade 7). In the Electricity Digital Lab, smartphone controls were divided between voltage/resistance and switch operations (Article 2). Inquiry knowledge assessment focused on variable identification. In Version A, 55% of students correctly named independent variables; in Version B, students tasked with identifying dependent variables continued to make conceptual and procedural errors after a teacher-led debrief. Common mistakes included copying a partner's response or naming non-variables such as room names or equipment labels. One student admitted, "My answer was wrong because neither of us really understood what was a dependent and what was an independent variable". These persistent errors demonstrate that external reflection and discussion alone are insufficient to establish a robust CVS understanding.

Study III: Genetics Simulation (Grade 9). The Genetics Digital Lab required partners to control distinct rabbit traits, compelling coordinated reasoning (Article 3). On the transfer-oriented inquiry task (K3), only 23.3% of students reached high performance, 46.5% performed at an average level, 20.9%

at a low level, and 9.3% did not respond. Although 81% achieved high performance on a basic inheritance question (K1), only 42% did so on a more abstract genetics problem (K2). Low-level inquiry responses often conflated outcomes with independent variables, for example stating, "The babies are the variable". These results confirm a pronounced theory–practice gap: foundational concepts did not reliably translate into complex experimental reasoning, even when collaboration was compulsory.

Cross-Study Synthesis. Across all three studies, inquiry performance remained modest, and variable identification emerged as the chief barrier. Although asymmetric roles successfully mandated collaboration and interdependence, they did not by themselves develop students' CVS skills. The consistent failure of passive definition delivery, even when reinforced by slide presentations and class discussions, reveals a need for active, scaffolded interventions.

4.3. Task-Performance Metrics and Error Patterns

A close examination of task-performance data and error analyses across the three TEAC studies reveals persistent challenges in students' experimental reasoning, collaboration, and communication.

Study I: Photosynthesis Simulation (Grades 5–6). In the Photosynthesis Digital Lab, errors were coded into three types, syntax, collaboration, and inquiry, based on systematic analysis of students' open-response answers (Article 1). Syntax errors reflected unclear phrasing, for example "bubbles coming" or "then bubbles come faster," which obscured the meaning of student observations. Collaboration errors occurred when a student answered the question intended for their partner instead of their own, indicating a breakdown in role-specific communication. Inquiry errors involved failures to isolate variables or to conduct controlled trials, such as reporting "Slowly in winter (every 10–30 s) but fast in summer (every 6 s)," which showed that learners altered multiple variables simultaneously and misread causal relationships. Error tallies varied by grade and group size. Fifth-grade dyads committed a total of 11 errors, whereas sixth-grade dyads committed only 2 errors. In contrast, fifth-grade quartets made 13 errors and sixth-grade quartets made 15. Although dyads tended to make fewer errors, the original analysis did not subject these error counts to statistical testing. Overall inquiry accuracy remained low across all groups, demonstrating that requiring students to manage distinct controls does not, by itself, eliminate fundamental reasoning mistakes.

Study II: Electricity Simulation (Grade 7). The Electricity Digital Lab study did not present specific error-reduction metrics, but qualitative reflections underscored trial-and-error strategies among low-performing pairs (Article 2). One student confessed, "Our answer was wrong because we did not study the scenario at all", and many groups tested random switch combinations without systematic planning or justification. These behaviours suggest that, even under

enforced collaboration, students may default to inefficient heuristics when stronger scaffolding is absent.

Study III: Genetics Simulation (Grade 9). In the Genetics Digital Lab, coordination difficulties persisted. Approximately 22% of students reported challenges in reaching consensus on experimental decisions, and 15% felt that collaboration occasionally slowed their progress (Article 3). These findings highlight that, although the asymmetric design compels interdependence, managing real-time negotiation and role coordination remains a substantial hurdle in smartphone-mediated inquiry contexts.

4.4. How Design Priorities Supported Knowledge Gains

The three TEAC studies demonstrate that asymmetric role assignments must be paired with explicit instructional supports to yield meaningful knowledge gains.

In Study II, seventh-grade learners used the Electricity Digital Lab with each partner controlling different circuit parameters. Although this arrangement enforced interdependence, many students initially conflated independent and dependent variables (Article 2). The subsequent teacher-led debrief was critical. During this session, the teacher revisited common misconceptions, linked students' worksheet answers to correct circuit logic, and guided them through reflective questions such as "Was your response correct or incorrect, and why?". Medium-performing pairs, in particular, demonstrated clearer variable reasoning and richer written reflections after the discussion. These qualitative improvements underscore that structural interdependence alone does not guarantee conceptual understanding; targeted debriefing and scaffolded reflection are essential to transform compelled collaboration into deeper understanding.

In Study III, ninth graders completed the Genetics Digital Lab and then engaged in a comprehensive reflection cycle. Students evaluated the accuracy of their responses across the three knowledge domains (K1, K2, and K3) and assessed the effectiveness of their collaboration in written reflections. A researcher subsequently applied the RRL coding protocol to these reflections, rather than prompting students to restate their original responses, to systematically chart metacognitive development (Article 3). For example, students were asked, "If your answer was correct, how did collaboration contribute to your success? If incorrect, what aspects of teamwork failed?". A moderate positive correlation ($r = .42$, $p < .05$) emerged between students' perceived collaboration benefits and their combined subject and inquiry knowledge scores, confirming that explicit interdependence together with structured reflection promotes robust cognitive engagement.

These findings reveal that TEAC's foundational design priorities, role asymmetry, contextualized teacher facilitation, and scaffolded reflection, must operate in concert. The asymmetric simulation compels F-F interaction, but it is through carefully orchestrated debriefings and reflection activities focusing on students' actual responses and collaborative processes that knowledge gains are realized.

5. FINDINGS II: Social Processes of Asymmetric Collaboration (Addressing RQ2)

This chapter examines how the TEAC design shaped students' collaborative processes during inquiry tasks. Drawing on self-reported measures of collaborative problem solving, systematic observation data, and qualitative reflections, four interrelated dimensions are examined. Section 5.1 presents students' ratings on CPS constructs, participation, perspective taking, social regulation and interdependence, and highlights observed behaviours that confirm or nuance these self-reports. Section 5.2 analyses the effects of structured role asymmetry on positive interdependence and error patterns. Section 5.3 considers how digital scaffolds and explicit prompts supported social regulation and perspective taking. Finally, Section 5.4 compares group configurations, showing how dyads and occasional triads navigated the asymmetric roles and what this implies for designing effective collaborative learning environments.

Table 5. *Self-Reported Collaborative Problem-Solving (CPS) Ratings*

Dimension	Study I (Gr 6)*	Study II (Gr 7)**	Study III (Gr 9)**
Information Sharing	6.9 (Dyads) vs. 5.4 (Quartets)	—	—
Mutual Support	6.9 (Dyads) vs. 5.2 (Quartets)	—	—
Participation	—	3.9	4.3
Perspective Taking	—	4.2	4.2
Social Regulation	—	4.1	4.4
Interdependence	—	3.8	3.8

*Note: *Study I used a 7-point scale. **Studies II and III used a 5-point scale.*

As shown in Table 5, dyads consistently reported higher levels of information sharing and mutual support in Study I, while ratings for perspective taking and interdependence remained relatively stable across Studies II and III.

5.1. Self-Reported CPS Dimensions and Observational Insights

Study I adapted Hinyard et al.'s (2018) self-assessment to measure information sharing, team support, and team learning (four items; Cronbach's $\alpha = .80$ for fifth graders, .83 for sixth graders). In Grade 6, dyads rated sharing and support significantly higher than four-person teams, with no differences emerging in Grade 5, as shown in Table 5. Analysis of students' open responses revealed concrete collaboration errors, such as a partner answering their teammate's

question verbatim, a sign that role asymmetry alone did not ensure effective information exchange (Article 1).

Study II employed a ten-item self-assessment: three subscales from ATC21S (participation $M = 3.9$; perspective-taking $M = 4.2$; social regulation $M = 4.2/4.1$) and an interdependence scale adapted from Van den Bossche et al. (2006)($M = 3.8/4.0$). Although the asymmetric design mandated positive interdependence, observers noted many pairs defaulted to unguided trial-and-error, testing random switch combinations without systematic re-testing or justification, and often misunderstood each other's roles. This mismatch helps explain why interdependence ratings lagged behind other dimensions. Crucially, some low-performing pairs nonetheless rated their collaboration highly, revealing a disconnect between perceived interpersonal harmony and actual task success. One student's reflection captured effective microskills: "Our answer was correct because we tested all different options and found the best one" (Article 2).

Study III employed a smartphone-based asymmetric simulation alongside a parallel ATC21S questionnaire with ninth graders ($N = 43$) to examine CPS in a biology lesson. Self-reports indicated strong engagement: 93% of students reported significant effort, 81% saw themselves as active participants, 88% worked to resolve disagreements constructively, and 77% revised their opinions when presented with new ideas. To validate these perceptions, the study also collected classroom observations and students' written reflections, triangulating multiple data sources. Observers noted frequent instances of students verbally summarizing their partner's reasoning before proceeding, confirming that high ratings for social regulation and perspective-taking reflected genuine interactive behaviours. Despite these strengths, a notable asymmetry emerged: 60% of students felt dependent on their partner's input, but only 42% believed their partner relied on them. This imbalance highlights a need for targeted scaffolding to promote balanced mutual reliance. Integrating self-reports, observations, and reflections provides a nuanced understanding of how structured interdependence supports engagement in participation and social regulation, yet also reveals challenges in mutual reliance and systematic problem solving that future instructional designs must address.

5.2. Role Asymmetry and Positive Interdependence Effects

Complementary role assignments compelled each student to hold unique information or controls and to share these with their partner, thereby fostering positive interdependence. In the photosynthesis simulation (Study I), sixth-grade dyads reported significantly higher mean ratings for information sharing ($M = 6.9$ vs. 5.4, $p < .001$), mutual support ($M = 6.9$ vs. 5.2, $p < .001$), and collective learning ($M = 6.1$ vs. 5.3, $p = .026$) compared to four-person teams. These dyads also committed only two total errors on combined subject knowledge tasks, substantially fewer than the 15 errors made by sixth-grade quartets, underscoring how role asymmetry can streamline collaboration and reduce performance errors.

In the electricity and genetics simulations (Studies II and III), students' self-reported interdependence scores were lower and more variable than other Collaborative Problem-Solving (CPS) dimensions, despite the asymmetric design requiring mutual reliance. In Study II, the interdependence subscale averaged 3.8–4.0 on a 5-point scale, which was comparable to participation ($M = 3.9$) but lagged behind perspective-taking ($M = 4.2$) and social regulation ($M = 4.1$–4.2). In Study III, only 42% of students felt their partner depended on them even though 60% acknowledged relying on their partner, revealing an asymmetry in perceived reciprocity. These findings suggest that alongside role asymmetry, targeted scaffolds, such as explicit prompts clarifying role dependence and pre-simulation activities on control-of-variables, are necessary to cultivate truly balanced interdependence.

5.3. Digital Scaffolds for Social Regulation and Perspective Taking

Across all three studies, students were instructed not to look at their partner's display and to "only talk about what you read or see on your own screen." Segmented interfaces and in-task prompts directed attention to each partner's unique controls and data. By enforcing this division of control, verbal explanation and joint reasoning became indispensable for completing each task. Structured worksheets and reflection questions reinforced these in-task prompts immediately after the simulation. In both studies, post-task worksheets asked students to evaluate the correctness of their responses and to explain how their partner's contributions influenced the outcome. By capturing peers' reasoning in writing, these reflection activities provided concrete examples for class discussion and debrief.

Teacher-led debrief sessions then drew on both simulation results and students' written reflections. In Studies II and III, the instructor reviewed common errors in identifying independent and dependent variables, demonstrated the correct answers, and asked students to explain whether their responses were correct and why. In Study III, these discussions were followed by researcher-led analysis using the RRL coding protocol to compare students' initial answers with observed outcomes and to explore how collaborative dialogue deepened their understanding.

Together these scaffolds supported students in regulating their collaboration and in taking their partner's perspective. Self-report data from Studies II and III show consistently high ratings for social regulation ($M = 4.2$–4.4) and perspective taking ($M = 4.1$–4.2) on 5-point scales. Observational notes confirmed that effective teams paused to summarize findings and to check mutual understanding. By making each partner's reasoning visible, whether on screen, on paper, or through facilitated dialogue, the TEAC design enabled learners to monitor and adjust their collaborative processes as an integral part of scientific inquiry.

5.4. Comparative Analysis Across Group Configurations

Only Study I systematically compared dyads with four-person teams. In that investigation, sixth-grade pairs reported significantly higher collaboration ratings and were observed to commit fewer errors than their four-person counterparts (though these error counts were not statistically tested), yet their superior combined inquiry task scores did not reach statistical significance across either grade cohort (Article 1). Studies II and III, by contrast, concentrated almost exclusively on two-person teams, with only three triads formed in each study to cover absences. Neither of these later studies included formal comparisons of different group sizes.

6. FINDINGS III: Metacognitive Regulation Through Reflection (Addressing RQ3)

This chapter examines how TEAC's reflective design elements supported metacognitive regulation during collaborative inquiry. Section 6.1 presents detailed outcomes from the RRL coding protocol for each knowledge dimension, using exact qualitative quotes for K1 where available and representative examples elsewhere. Sections 6.2–6.4 then trace the evolution of reflection quality, describe technology-mediated scaffolds, and link reflection to performance outcomes.

6.1. Remember-Recall-Learning (RRL) protocol

Table 6. *Distribution of RRL Reflection Indicators (Study III)*

Knowledge Domain	Remember (Recall Accuracy)	Recall (Judgment of Correctness)	Learning (Evidence of Growth)
K1 (Basic)	79.1% Complete	74.4% Accurate	76.7% Visible Growth
K2 (Conceptual)	48.8% Complete	46.5% Accurate	41.9% Visible Growth
K3 (Inquiry)	41.9% Complete	48.8% Accurate	51.2% Visible Growth

As shown in Table 6, the distribution of reflection indicators across knowledge domains reveals a differentiated role of reflection in basic, conceptual, and inquiry learning The table illustrates a clear gradient, with higher accuracy and learning visibility in K1 and progressively weaker outcomes in K2 and K3. This pattern supports the interpretation that reflective scaffolding was more effective for consolidating factual knowledge than for supporting inquiry-related reasoning.

In Study III, students' metacognitive reflections were systematically analysed using the RRL coding protocol (Rannastu-Avalos et al., 2025). When evaluating subject knowledge recall (K1), a clear majority of students provided full reproduction of their initial responses, with 79.1% offering complete answers, while only 4.7% each produced incomplete or incorrect recollections; 11.6% did not respond at all. In the subsequent recall phase, 74.4% accurately judged their own correctness, 23.3% recognized errors in their responses, and a small minority (2.3%) omitted judgments entirely. Finally, evidence of conceptual refinement was visible for 76.7% of students, indicating that most learners refined their understanding after reflection, whereas 23.3% showed no detectable learning gains. Exemplary student remarks, such as "Yes, our answer was correct. We both remembered Aa × Aa could lead to 25% white" and "Now I understand that when both rabbits are Aa, they can produce white offspring (aa)", illustrate the depth of engagement that this reflection process elicited.

Conceptual understanding (K2) proved more variable. Less than half of the cohort (48.8%) produced complete conceptual explanations upon first recall,

9.3% offered partial accounts, and 4.7% answered incorrectly; 37.2% again provided no response. When judging the accuracy of their explanations, 46.5% correctly identified whether their initial reasoning was valid, while 37.2% misjudged their own performance, and 16.3% did not attempt a judgment. Only 41.9% demonstrated visible conceptual growth during the learning phase, suggesting that deeper understanding of genetics concepts emerged for fewer than half of the students.

Inquiry knowledge (K3), the ability to identify and reason about experimental variables, posed the greatest challenge. In the remember phase, 41.9% of students correctly listed both independent and dependent variables, 37.2% offered incomplete listings, and 2.3% were entirely incorrect; 18.6% left this question blank. During recall, 48.8% accurately judged their variable identifications, whereas 39.5% believed their answers were correct when they were not, and 11.6% did not respond. Encouragingly, 51.2% of students evidenced conceptual gains by refining their inquiry strategies, but 48.8% showed no visible improvement. Representative reflections, "Independent variable is fur colour, dependent variable is offspring ratio" contrasted with "Dependent variable is parent genotype", underscore the variability in application of experimental design principles.

Notably, 15% of participants reported that the collaborative process occasionally hindered their progress, highlighting the tension between social coordination and cognitive demands in time-limited tasks (Rannastu-Avalos et al., 2025). Overall, these findings demonstrate that structured reflection prompts, while highly effective for reinforcing basic subject knowledge, yield more mixed results when applied to higher-order conceptual and inquiry-based learning.

6.2. Evolution of Reflection Quality from Study I to III

The three iterations of DBR reveal a clear trajectory in the sophistication of metacognitive support. In Study I, reflection was essentially absent: the photosynthesis simulation offered no in-task or post-task prompts for students to evaluate their planning, strategies, or outcomes, yielding only the minimal insights afforded by a general collaboration questionnaire. Study II introduced structured, external reflection prompts via paper worksheets and a teacher-led debrief. These questions directed students to judge the correctness of their experimental answers, analyse their collaboration, and consider challenges such as variable identification and time management. Qualitative evidence shows that even low-performing pairs deepened their conceptual understanding following this explicit reflection phase. By Study III, reflection scaffolding had matured into a multi-indicator system. The RRL coding protocol systematically captured three distinct metacognitive stages – accurate reproduction of initial responses, evaluative judgments of those responses, and evidence of conceptual growth – revealing richer metacognitive regulation and strategic revision than ever before. Together, these studies illustrate how embedding progressively structured reflection supports can enhance students' capacity to regulate their own learning and collaboration.

6.3. Staged Development of Reflection Scaffolding

The three studies illustrate a deliberate progression in the design of reflection support, moving from implicit to explicit prompts and from minimal to richly structured metacognitive analysis, even though all reflection scaffolds remained external to the simulation interface.

Study I: Photosynthesis Simulation. In the Photosynthesis Digital Lab (Study I; Rannastu-Avalos et al., 2019), collaboration emerged solely from the asymmetric task design: one student controlled lamp intensity while the other controlled season. No in-simulation prompts guided learners to evaluate their reasoning. Instead, reflection took place after the activity via open-response questions on printed worksheets, and collaboration was assessed through a paper-based self-report questionnaire, followed by a teacher-led debrief.

Study II: Electricity Simulation. The Electricity Digital Lab (Study II; Rannastu-Avalos et al., 2023) retained the smartphone-based asymmetric controls but introduced explicit, structured reflection. Immediately after the simulation, students completed printed worksheets that asked them to judge the correctness of their answers ("Were your responses to the worksheet questions correct or incorrect?") and to evaluate their collaboration ("What do you consider a successful collaboration?"). A subsequent class discussion, led by the teacher, reinforced SSRL by debriefing both cognitive and interactional aspects of performance.

Study III: Genetics Simulation. In the Genetics Digital Lab (Study III; Rannastu-Avalos et al., 2025), the asymmetric design once again required partners to coordinate decisions. After the simulation, students completed domain-specific open-ended questionnaires that prompted them to evaluate their worksheet responses across K1, K2, and K3 and to reflect on how their collaboration influenced those outcomes. A researcher then applied the RRL coding protocol to these reflection artifacts and original worksheet answers, systematically assessing metacognitive accuracy and conceptual growth. Although the worksheets remained outside the smartphone-based interface, their timing and structure ensured that reflection formed a central, rigorously evaluated phase of the learning sequence.

Across the three studies, four central developmental trends can be identified. First, the approach moved from implicit to explicit prompting, as the initial reliance on task structure was gradually replaced by carefully designed reflection questions that directly guided learners' metacognitive regulation. Second, reflection progressed from an unstructured format to a structured process, with minimal post-task self-assessment in the early stage giving way to standardized questionnaires and systematic debrief protocols in later studies. Third, the analytical focus advanced from basic to nuanced forms of analysis, shifting from general self-reports to multi-indicator metacognitive frameworks capable of capturing more precise and differentiated aspects of learners' regulation processes. Fourth, the role of technology remained central in providing the asymmetric task context through the simulation platform, while the accompanying reflection

scaffolds, although initially external to the platform, became increasingly sophisticated and integral to the overall pedagogical design.

This trajectory reflects a strategic shift towards a holistic inquiry environment in which collaboration, cognitive processing, and metacognitive reflection are systematically interwoven, even when the reflective prompts operate outside the real-time simulation interface.

6.4. Comparative Effectiveness of Digital Scaffolds

Across the three TEAC studies, the core digital scaffolds, segmented interfaces (asymmetric task design), shared visualizations, and pedagogical interaction scripts (in the form of reflection prompts), demonstrated evolving effectiveness in supporting inquiry and collaboration.

Study I: Photosynthesis Simulation. In the Photosynthesis Digital Lab, the asymmetric iPad interface itself served as the primary scaffold. One student controlled season and the other lamp intensity, creating positive interdependence by design. Both partners viewed the combined effects on their screens, which implicitly required communication but offered no in-simulation prompts for reflection. Post-task, students completed open-response questions on paper and participated in a teacher-led debrief. Although this structure compelled basic collaboration, inquiry performance remained low (28% for Grade 5, 40% for Grade 6) and variable control proved challenging.

Study II: Electricity Simulation. The Electricity Digital Lab extended asymmetric control to smartphones, with one student managing voltage and resistance, the other switching components. Shared visual feedback on circuit behaviour sustained joint reasoning. Crucially, explicit reflection prompts appeared on printed worksheets immediately post-task, questions such as "Were your responses correct or incorrect?" and "What constitutes successful collaboration?", and a subsequent class discussion reinforced socially shared regulation. Despite highly rated perspective-taking and social regulation (means > 4.0), many students still struggled to identify independent vs. dependent variables, and interdependence perceptions remained uneven.

Study III: Genetics Simulation. In the Genetics Digital Lab, asymmetric controls over complementary traits, such as fur colour versus ear shape, continued to compel interdependent verbal and digital coordination, while shared offspring phenotype displays reinforced collaborative analysis. Reflection support remained external to the simulation: students completed domain-specific open-ended questionnaires after the activity, and a researcher then applied the RRL coding protocol to those responses. Prompts required learners to evaluate their worksheet performance, compare observed inheritance patterns with their initial answers, and articulate revised strategies. Results showed strong gains in subject knowledge (81% for K1), persistent inquiry challenges (23% for K3), and greater visible growth in inquiry competence (51%) than in advanced conceptual understanding (42%). Measures of social regulation (M = 4.4) and perspective taking (M = 4.2) remained high, yet only 42% of students experienced true reciprocal

dependence. This combination of asymmetric task design and structured reflection highlights that while structural interdependence effectively drives interaction, further scaffolding is required to bridge the gap between social coordination and deep inquiry skills.

Synthesis. Across the three DBR cycles, the TEAC framework evolved in ways that progressively deepened both the pedagogical supports and the methodological precision of the research design. One of the most significant shifts was the move from implicit to explicit scaffolding. In Study I, the only guidance provided was embedded within the task structure itself, relying on the affordances of role asymmetry to promote collaboration. In contrast, Studies II and III introduced layered, structured reflection prompts, signalling a deliberate emphasis on supporting students' metacognitive regulation.

The design of reflection activities also advanced markedly, evolving from unstructured to structured reflection. In Study I, opportunities for reflection were limited to a brief, unstructured post-task phase. By Study II, this had been replaced with standardized reflection worksheets and immediate teacher-led debrief discussions following the simulation, ensuring that insights were consolidated while the learning experience was still fresh. Study III extended this approach further by incorporating domain-specific questionnaires completed after the Genetics Digital Lab and by systematically applying the Remember–Recall–Learning (RRL) coding protocol to both the reflections and the original worksheet responses. This trajectory, from minimal prompts to rigorously analysed, multi-stage reflection cycles, demonstrates the increasing priority given to metacognitive support across the research programme.

Similarly, the analysis of metacognitive processes matured from basic to nuanced metacognitive analysis. Early stages of the research relied on general self-reports, which provided useful but coarse-grained insights. By Study III, these had been replaced by multi-indicator reflection coding, enabling the measurement of both metacognitive accuracy and the extent of conceptual gains with far greater precision.

Finally, technology's role within the TEAC framework also evolved in response to empirical findings. Across all three studies, simulations served as the primary technological medium, first delivered via shared tablets and later via smartphones. In Study I, tablet-based labs allocated distinct controls to each student and provided shared visual feedback. Study II adapted the design for smartphone delivery, with post-simulation paper-based reflections and teacher-led debriefs as the main supports. Study III retained the smartphone format but combined it with open-ended reflections collected after the lesson and analysed using the RRL protocol. This progression illustrates how the integration of familiar devices with increasingly structured, post-simulation supports strengthened both collaborative inquiry and metacognitive development over time.

Despite these advances, students' grasp of variable control and their perception of mutual interdependence remained challenging, indicating the need for additional pre-simulation activities and explicit interdependence mapping to bridge structural design with learners' metacognitive and social engagement.

6.5. Links Between Reflection and Performance

Both qualitative observations and quantitative analyses converge to demonstrate the pivotal role of structured reflection in enhancing collaborative inquiry outcomes. In Study II, although no statistical correlation was calculated, observations and debrief comments indicated improved understanding of variables and role coordination, with students crediting experimentation and clear communication and highlighting the importance of the debrief.

During this session, the instructor highlighted common errors in variable identification, guided pairs through the correct circuit logic, and posed reflective questions such as "Was your answer correct or incorrect, and why?" Medium-scoring teams exhibited more accurate reasoning about independent and dependent variables, and even low-performing dyads showed measurable conceptual improvements following the discussion.

In Study III, these qualitative insights are confirmed quantitatively: a moderate positive correlation ($r = .42$, $p < .05$) emerged between students' self-reported benefits of collaboration and their combined subject and inquiry knowledge scores, indicating that deeper engagement with reflective prompts is associated with superior academic performance. Yet, 15% of participants noted that collaboration occasionally slowed their progress, underscoring the difficulty of synchronizing cognitive processing with social negotiation under time constraints.

Taken together, these findings affirm that metacognitive regulation, fostered through carefully scaffolded reflection, is essential both for refining students' scientific reasoning and for deepening the quality of their collaborative interactions.

7. DISCUSSION

This chapter provides an integrative synthesis of the empirical findings from Studies I–III and interprets them through the theoretical lens of the TEAC framework's three interlocking learning mechanisms: Knowledge Construction (cognitive mechanism), Collaborative Interaction (social mechanism), and Regulation Through Reflection (metacognitive mechanism). While the results were reported across three empirical chapters organized by learning processes, the present discussion is structured to explicitly answer the thesis's three research questions in order to strengthen the alignment between the empirical evidence and the overarching design argument.

The TEAC framework conceptualizes collaborative inquiry as a system of interdependent processes rather than independent components. Cognitive engagement (RQ1) establishes whether the task configuration is operable at all; social interaction (RQ2) determines how knowledge is constructed within that configuration; and metacognitive regulation (RQ3) shapes how these experiences are monitored, evaluated, and consolidated over time. Importantly, these processes do not function in isolation: limitations at the cognitive level constrain interaction, interaction quality conditions learning outcomes, and reflective regulation feeds back into both cognitive and social processes.

7.1. RQ1: Group Configuration as a Design Condition for Asymmetric Digital Inquiry

Research Question 1 examined how group size influences students' inquiry performance and collaborative dynamics in technology-enhanced asymmetric simulation tasks. Within the design-based research (DBR) logic, this question served as a calibration step: before refining role asymmetry and reflection, it was necessary to establish the social configuration in which the TEAC design could operate with feasible coordination demands (Rannastu et al., 2019).

Evidence from Study I indicated that dyadic configurations supported more coordinated inquiry activity than four-person groups under asymmetric conditions. In the Photosynthesis Digital Lab, sixth-grade dyads achieved higher raw performance on combined inquiry tasks (61% correct) than quartets (40%), and classroom observations documented substantially fewer procedural errors in dyads (2) than in sixth-grade quartets (15) (Rannastu et al., 2019). Although differences in inquiry performance were not statistically significant and the observational error counts were not analysed with inferential statistics, the combined pattern across outcome and process indicators suggested that dyads reduced coordination costs and supported more focused interaction than larger teams (Rannastu et al., 2019).

From a theoretical perspective, the observed advantage of dyads can be interpreted using CLT as a design-oriented explanation, not as a measured effect. Sweller (1988) and Kalyuga et al. (2003) argue that unguided search and

coordination can impose heavy working memory demands that interfere with schema acquisition, particularly for novice learners. In technology-mediated inquiry, these coordination demands can become collaborative as well as cognitive, meaning that increases in group size may raise extraneous load through communication and synchronization requirements. The TEAC design intentionally distributes control and information to structure interaction, yet Study I suggests that larger groups may introduce social and procedural overhead that competes with conceptual processing, thereby limiting the intended benefits of asymmetric task designs (Kalyuga et al., 2003; Sweller, 1988).

Importantly, the RQ1 findings informed a clear DBR design decision. Following Study I, group size comparisons were discontinued, and dyads were adopted as the standard configuration in Studies II and III (Rannastu-Avalos et al., 2023; Rannastu-Avalos et al., 2025). This was not an omission but an empirically motivated refinement that stabilized the "social container" of the intervention so that later cycles could concentrate on the mechanisms most central to TEAC's maturation, namely the quality of role-based interaction and reflective regulation (Rannastu et al., 2019). In this sense, group configuration should be treated as a design condition that enables or constrains subsequent mechanisms, rather than as the primary explanatory mechanism of learning itself. By establishing dyads as the most cognitively feasible configuration for asymmetric inquiry, RQ1 defines the conditions under which meaningful collaborative interaction can occur, thereby enabling the social processes examined in RQ2.

7.2. RQ 2: The Impact of Structured Role Distribution on Co-Construction

Research Question 2 investigated how structured role asymmetry influenced students' ability to co-construct knowledge and solve problems collaboratively. This question addressed the core TEAC mechanism: the design of information gaps and distributed control intended to foster positive interdependence and sustained negotiation. In this context, a distinction is made between social interaction (the coordination of actions and communication) and the co-construction of knowledge (the epistemic intersection where individual cognitive contributions are integrated through social interaction into a shared understanding).

Across Studies II and III, structured role distribution consistently compelled students to coordinate actions and exchange information. In the Electricity Digital Lab, complementary controls required partners to negotiate parameter changes in order to reach correct circuit solutions, and students reported high levels of perspective taking and social regulation (Rannastu-Avalos et al., 2023). This pattern is consistent with the cooperative learning claim that interdependence becomes more robust when task completion cannot be achieved by an individual working alone (Johnson & Johnson, 1999). It also aligns with process-oriented accounts of collaboration that emphasize the construction of a shared problem space through coordinated, synchronous activity (Roschelle & Teasley, 1995)

and the importance of establishing shared mental representations during collaborative reasoning (Lu & Bulut, 2024).

At the same time, the findings indicate that interaction is not synonymous with disciplined inquiry. While role asymmetry effectively ensured participation and negotiation, it did not reliably produce advanced inquiry reasoning. Study II showed that even in active dyads, students' understanding of the relationships between independent and dependent variables required additional instructional support (Rannastu-Avalos et al., 2023). Study III further demonstrated that high levels of engagement and reported collaboration benefits were compatible with uneven inquiry performance, particularly in tasks demanding sophisticated control-of-variables reasoning (Rannastu-Avalos et al., 2025). This pattern supports broader evidence that high-quality collaboration depends on more than interaction frequency, and requires structured support for shared understanding, co-regulation, and conceptual integration (Baucal et al., 2023; Roschelle & Teasley, 1995).

These results also warrant a cautious reading of claims that asymmetry inherently improves learning. Kozlov and Große (2016) report that asymmetrical distributions of propositional knowledge do not necessarily yield higher learning gains than symmetrical pairings, and that reciprocal exchange may be more reliable in symmetrical conditions. Similarly, Burns et al. (2024, 2025) argue that symmetrical peer interaction can foster more authentic negotiation and exploratory talk than interactions shaped by rigid asymmetries. From a TEAC perspective, these sources do not invalidate structured role design, but they sharpen the conclusion that asymmetry functions as a catalyst for interaction rather than a guarantee of knowledge co-construction.

Finally, the findings highlight sensitivity to group dynamics even within dyads. Collaboration outcomes can be shaped by dominance and uneven participation, particularly in tasks with high interdependence (Rojas et al., 2021; Rosen et al., 2020). This underscores why TEAC's role structure cannot be treated as sufficient on its own. Instead, role asymmetry appears most productive when it is accompanied by supports that foster equitable participation, help students externalize reasoning, and sustain shared conceptual focus (Care, 2018; Hesse et al., 2015; Stahl et al., 2005). In sum, the answer to RQ2 is that structured role distribution reliably enforces interdependence and activates collaborative interaction, but it must be coupled with cognitive and metacognitive supports to ensure that interaction becomes inquiry. These findings indicate that social interaction functions not merely as a context for learning, but as a mechanism through which cognitive work is distributed and coordinated, creating the need for the reflective regulation examined in RQ3.

7.3. RQ3: The Role of Reflective Practices in Supporting Metacognitive Regulation

Research Question 3 examined how reflective practices and digital prompts support students' metacognitive regulation during collaborative inquiry. This question addresses the mechanism through which collaborative activity is transformed into learning, namely students' capacity to monitor, evaluate, and regulate their reasoning and collaboration over time (Järvelä et al., 2016; Schraw et al., 2006).

Study III provided the strongest evidence for this mechanism through the structured Remember–Recall–Learning (RRL) protocol (Rannastu-Avalos et al., 2025). The reflection data showed that students could articulate what they had done, evaluate correctness, and, in many cases, indicate changes in understanding. Importantly, the RRL protocol elicited visible learning gains in 76.7% of students, while outcome patterns indicated strong conceptual recall (81% high-level K1), more uneven conceptual understanding (42% high-level K2), and comparatively limited advanced inquiry performance (23% at advanced K3) (Rannastu-Avalos et al., 2025). This distribution suggests that reflective scaffolding supported consolidation most strongly at the level of recall and conceptual clarification, while transfer to higher-order inquiry remained difficult.

These findings align with established claims that structured reflection supports metacognitive awareness and deeper learning by prompting evaluation and monitoring processes that would otherwise remain implicit (Järvelä et al., 2016; Schraw et al., 2006). They also match the broader DBR-based argument that inquiry learning in complex domains requires structural supports to avoid procedural engagement without conceptual progress (de Jong et al., 2021; de Jong et al., 2023). From this perspective, reflection should not be treated as an add-on, but as an integral mechanism that supports constructive engagement and helps students convert interaction into conceptual insight.

The present findings also resonate with research on technology-mediated collaborative learning showing that interactional and regulatory challenges, such as unequal participation and peripheral roles, are a persistent risk in collaborative activity and are unlikely to resolve spontaneously without deliberate scaffolding (Channa et al., 2025; Latva-aho et al., 2025). In line with these findings, the structured reflection embedded after the asymmetric inquiry tasks appeared to function as a mechanism for rendering such challenges visible and regulatable. This supports earlier work suggesting that reflective scaffolds enable learners to articulate, attribute, and jointly examine difficulties that tend to remain implicit during task performance itself (Näykki et al., 2021).

In addition, triangulation of self-reported regulation with performance-based worksheet data revealed meaningful discrepancies that further clarify the role of reflective practices in metacognitive regulation. In several cases, students reported high levels of participation, social regulation, and perceived interdependence, while nevertheless demonstrating weak inquiry performance or incomplete

conceptual understanding in the worksheet tasks. Rather than indicating measurement inconsistency, these mismatches were treated as analytically informative, pointing to situations in which regulation was experienced subjectively but did not yet function as epistemically productive regulation. From an RQ3 perspective, this pattern suggests that metacognitive regulation becomes consequential for learning outcomes only when it is sufficiently scaffolded to support not merely awareness and reflection, but also the translation of evaluative insight into improved inquiry decisions and variable reasoning. In this sense, triangulation served not only as a validation strategy, but as a substantive lens for identifying the boundary conditions under which reflective regulation supports learning.

At the same time, the persistence of uneven inquiry outcomes suggests a continuing theory–practice gap: students may be able to evaluate their work without consistently translating that evaluation into improved inquiry design and variable reasoning. Related research similarly notes that learners can struggle to apply abstract reasoning across contexts, especially when tasks require coordinated transfer of conceptual and procedural knowledge (Herro et al., 2021; Kapici, 2025). This supports the implication that future TEAC iterations should increasingly integrate reflective and metacognitive prompts into critical decision points within the inquiry flow, rather than relying mainly on post-task reflection (Diefes-Dux & Stratman, 2022; Pei et al., 2020; H.-S. Wang et al., 2021).

Finally, the synergy argument central to TEAC is supported by the association between perceived collaboration benefits and learning outcomes. In Study III, students' perceived collaboration benefits correlated positively with combined knowledge scores, suggesting that students who recognized and regulated the value of collaboration tended to achieve stronger learning outcomes (Rannastu-Avalos et al., 2025). Interpreted within the TEAC logic, reflective regulation appears to function as a coupling mechanism that helps align the social dynamics of collaboration with cognitive outcomes.

7.4. Integrated Implications and Contributions of the TEAC Framework

Synthesizing the answers across RQ1–RQ3 highlights the interdependence of TEAC's learning mechanisms. Dyadic configuration established manageable coordination demands (RQ1), structured role asymmetry activated interdependence and interaction (RQ2), and structured reflection supported regulation and consolidation of learning (RQ3) (Rannastu et al., 2019; Rannastu-Avalos et al., 2023, 2025). Across the three DBR cycles, the framework therefore matured not as a fixed instructional recipe but as a set of design principles specifying how social configuration, task structure, and reflective regulation must be orchestrated to function in authentic classroom settings (Brown et al., 1989; Vygotsky, 1980).

The thesis's design choices gain additional clarity when considered in relation to the selected content domains. Photosynthesis, electricity, and genetics are well

documented as conceptually demanding topics involving abstract, largely non-observable phenomena that often generate persistent non-normative ideas and reasoning difficulties (Pei et al., 2020; Popov et al., 2018; Sui et al., 2022). These domains are therefore appropriate testbeds for TEAC, because they allow examination of whether technology-enhanced, structurally guided collaboration can support learning processes that are particularly vulnerable to superficial engagement when inquiry is insufficiently supported (de Jong et al., 2023; Lazonder & Harmsen, 2016). In this sense, the domain progression across the three studies does not merely provide varied contexts, but functions as a systematic test of TEAC under increasing conceptual complexity (Rannastu et al., 2019; Rannastu-Avalos et al., 2023, 2025).

At the theoretical level, the results support a design-oriented interpretation of cognitive and collaborative load distribution. Accounts of collaboration as a collective information-processing system suggest that distributing information and task demands across partners can expand functional working memory and reduce individual overload, especially when the interface and scaffolds operate as shared cognitive resources (Guzmán & Zambrano, 2024; Orbegoso-Dávila et al., 2024; Sankaranarayanan et al., 2021). TEAC operationalizes this principle through complementary controls and distributed representations, while simultaneously acknowledging that these benefits depend on boundary conditions such as group composition, participation equity, and the presence of prompts that guide reasoning and regulation (Care, 2018; Rojas et al., 2021; Rosen et al., 2020).

At the practical level, the integrated findings suggest that TEAC is most defensible as a coherent orchestration model: (a) dyads reduce coordination overhead and stabilize role enactment; (b) role asymmetry prevents free-riding and compels negotiation; and (c) structured reflection strengthens metacognitive regulation and helps students convert collaborative activity into conceptual learning (Järvelä et al., 2016; Johnson & Johnson, 1999; Schraw et al., 2006). This implication aligns with research emphasizing that the quality of collaboration is enhanced when interaction is supported by scripts, prompts, and structured opportunities for co-regulation rather than left to emerge spontaneously (Hesse et al., 2015; Jeong & Hmelo-Silver, 2016; Stahl et al., 2005). It also points towards design refinements that move beyond participation metrics to support conceptual depth and transfer in inquiry tasks (Andrews-Todd et al., 2022; Cheruiyot & Molnár, 2025; Çini et al., 2023; Du et al., 2023; Pásztor-Kovács et al., 2023; Sun et al., 2022; C. Wang et al., 2023).

Taken together, the thesis contributes a validated design account of how asymmetric digital collaboration can be made workable in real classrooms, while also clarifying its limits. The evidence indicates that asymmetry reliably produces interaction, but that interaction becomes learning only when regulation is deliberately supported, and when inquiry reasoning is scaffolded at the points where students must identify variables, justify decisions, and connect representations to scientific principles (de Jong et al., 2021; Diefes-Dux & Stratman, 2022; H.-S. Wang et al., 2021).

7.5. Theoretical Contributions

The central theoretical contribution of this thesis is the articulation and empirical refinement of the TEAC framework as a design model that integrates four foundational traditions – social constructivism, CLT, CSCL, and IBL – into a coherent orchestration logic for asymmetric, technology-mediated collaboration in authentic science classrooms (Brown et al., 1989; de Jong et al., 2021; Pedaste et al., 2015; Sweller, 1988; Vygotsky, 1980). Across three design-based research cycles, TEAC was not treated as an abstract set of principles but as a progressively refined intervention, where design decisions were iteratively adjusted in response to classroom evidence, thereby strengthening the explanatory precision of how asymmetric collaboration can be made workable under realistic instructional constraints (Brown et al., 1989).

Social constructivism operationalized through designed interdependence. Within a social constructivist tradition, TEAC advances the argument that productive collaborative inquiry does not emerge reliably from group work alone, but requires deliberate design of conditions that make joint meaning-making necessary (Vygotsky, 1980). TEAC operationalizes this claim by orchestrating asymmetric roles through distributed control and complementary information, thereby creating information gaps that require students to externalize partial ideas, articulate reasoning, and negotiate shared interpretations rather than working in parallel (Rannastu et al., 2019; Rannastu-Avalos et al., 2023). This mechanism is consistent with the social constructivist emphasis on development through interaction in the Zone of Proximal Development, where dialogue and mediation enable learners to achieve what would not be accessible individually (Vygotsky, 1980), and it aligns with classroom-oriented constructivist accounts that treat learning as situated in designed activity systems rather than isolated cognition (Brown et al., 1989).

The empirical contribution of Study I is that it makes visible a boundary condition often assumed but seldom demonstrated in classroom contexts. Rannastu et al. (2019) show that when collaboration is left structurally underdetermined, negotiation can fail even when learners are placed into groups, as indicated by substantially higher procedural error counts in larger unstructured group configurations compared with asymmetric dyads. This pattern supports the position that TEAC advances social constructivism not by simply increasing interaction opportunities, but by designing the participation architecture that makes interaction functionally necessary for progress within the task (Rannastu et al., 2019).

At the same time, the thesis positions designed asymmetry as a calibrated strategy rather than an unconditional good. Kozlov and Große (2016) caution that knowledge-asymmetric dyads do not automatically yield superior learning gains and that reciprocal exchange can be more reliable under symmetrical knowledge distributions when mutual understanding is the primary goal. Similarly, Burns et al. (2024, 2025) emphasize that symmetrical peer interaction often supports more authentic negotiation and exploratory dialogue than interaction shaped by rigid

asymmetries. TEAC responds to these boundaries by framing asymmetry as a catalyst for exchange that must be supported by interaction scaffolds that protect reciprocity, including communication scripts, shared-understanding checkpoints, and symmetrical goal structures that align individual contributions with joint outcomes (Care, 2018; Jeong & Hmelo-Silver, 2016; Stahl et al., 2005).

CLT applied as a design rationale, not a measured outcome. Sweller (1988) and Kalyuga et al. (2003) argue that novices can be overloaded by unguided problem solving because heavy working memory demands impede schema acquisition. TEAC incorporates this logic by distributing task demands and informational access across partners, integrating related controls and labels to reduce split-attention demands and providing structured prompts that reduce inefficient means-ends search processes that can consume cognitive resources without producing learning (Kalyuga et al., 2003; Sweller, 1988).

However, this thesis does not claim to have measured cognitive load directly. CLT therefore functions here as a design rationale and interpretive lens for why the TEAC interface and role structure were built as they were, rather than as an empirically verified mechanism of load reduction in the strict measurement sense (Sweller, 1988, 2022). This distinction is important for methodological transparency and strengthens the theoretical contribution by keeping claims commensurate with evidence.

CSCL and collaborative cognitive load as an interaction-sensitive refinement. Within the CSCL tradition, TEAC adds nuance to the claim that collaboration can function as an extended cognitive workspace by showing that distributed control can both enable and burden learners depending on interaction costs. Guzmán and Zambrano (2024) describe groups as information-processing systems in which cognitive resources can be distributed. Orbegoso-Dávila et al. (2024) and Sankaranarayanan et al. (2021) similarly argue that collaboration can mitigate individual working memory limitations through collective processing. TEAC operationalizes this assumption by ensuring partners must coordinate complementary actions, such as parameter changes across distributed controls, while both view the shared effects of those actions in the simulation environment (Rannastu-Avalos et al., 2023).

Recent evidence also emphasizes that collaborative settings can introduce transaction costs, including coordination and communication demands that can offset load-reduction benefits under certain task conditions (Du et al., 2023). TEAC addresses this risk through design choices that contain interaction costs without eliminating interaction itself, including explicit communication scripts and shared-understanding checkpoints that stabilize turn-taking and reduce non-productive coordination overhead (Jeong & Hmelo-Silver, 2016; Stahl et al., 2005). In this way, TEAC contributes to CSCL by specifying the design conditions under which collaboration is more likely to function as productive joint cognition rather than as a source of additional cognitive burden.

Inquiry-Based Learning strengthened through structural guidance and embedded reflection. Finally, TEAC contributes to IBL by operationalizing inquiry as a structured cycle in which collaboration, technology mediation, and

reflection are designed to work together rather than being treated as loosely connected instructional components. TEAC aligns with the inquiry phases specified by Pedaste et al. (2015) and responds directly to the gap between inquiry theory and classroom practice documented in design-oriented IBL research (de Jong et al., 2021). At the level of evidence-based rationale, TEAC is consistent with meta-analytic findings showing that inquiry yields positive outcomes primarily when supported by explicit guidance, and that open inquiry without sufficient support can be negatively associated with achievement (de Jong et al., 2023; Lazonder & Harmsen, 2016).

The thesis also grounds this rationale in domain selection. Photosynthesis, genetics, and electricity are conceptually demanding, non-observable domains where students frequently hold persistent non-normative ideas and where abstract relationships are difficult to articulate and regulate during inquiry (Pei et al., 2020; Popov et al., 2018; Sui et al., 2022). This makes them appropriate testbeds for TEAC because they allow examination of whether structurally guided, technology-enhanced collaboration can support conceptual learning where minimally guided inquiry is especially vulnerable to superficial procedural engagement (de Jong et al., 2021, 2023).

7.6. Design Guidelines for Practitioners

The findings across Studies I–III translate into a set of practical guidelines that support teachers in implementing asymmetric collaborative simulations as a feasible classroom approach. The first guideline concerns group configuration. Study I indicates that dyads were more workable than four-person teams under asymmetric simulation conditions, as reflected in higher raw inquiry performance and substantially fewer procedural errors, although group differences in inquiry performance were not statistically significant and the observational error counts were not tested inferentially (Rannastu et al., 2019). In classroom terms, dyads appear to provide a clearer role ecology in which both students remain accountable and coordination demands remain manageable.

A second guideline is that role asymmetry should be designed to enforce positive interdependence rather than merely distribute tasks. Johnson and Johnson (1999) define positive interdependence as a perception that success depends on one another, and TEAC implements this by ensuring partners control different variables and hold complementary information so that neither can complete the inquiry alone (Rannastu-Avalos et al., 2023). In the Electricity Digital Lab, this design was operationalized through complementary control of key parameters that required negotiation to reach correct circuit configurations (Rannastu-Avalos et al., 2023). The practical implication is that teachers should design role splits that make joint decision-making necessary at meaningful decision points, rather than dividing labour in ways that allow parallel completion.

A third guideline is that technology should be used as both a cognitive and social scaffold. CSCL research has long emphasized that digital environments

can shape interaction by structuring participation and focusing attention (Stahl et al., 2005). In TEAC, prompts that constrain what students report from their own view and require information sharing function as participation scaffolds that support perspective-taking and reduce unproductive overlap (Jeong & Hmelo-Silver, 2016). This logic is also consistent with collaborative cognitive load accounts that treat shared representations and distributed information as a joint resource when interaction is well managed (Guzmán & Zambrano, 2024; Orbegoso-Dávila et al., 2024; Sankaranarayanan et al., 2021).

A fourth guideline concerns reflection as an essential component of lesson design rather than an optional closure activity. In Study III, structured reflection using the Remember–Recall–Learning protocol made learning processes visible and supported measurable consolidation patterns, including visible learning gains in 76.7% of students alongside high-level recall and more uneven conceptual and inquiry outcomes (Rannastu-Avalos et al., 2025). Schraw et al. (2006) position reflection as a central mechanism for metacognition, and Järvelä et al. (2016) argue that regulatory prompts can increase awareness of both one's own and others' learning processes. The design implication is that reflection should be scheduled as a substantive portion of the lesson and structured with prompts that require students to evaluate correctness, justify revisions, and connect collaborative actions to scientific reasoning (Järvelä et al., 2016; Schraw et al., 2006).

Finally, practitioners benefit from a multidimensional assessment strategy that captures cognitive, social, and metacognitive processes. TEAC's approach to triangulation, combining task outcomes, CPS self-evaluations, and reflection data, provides teachers with evidence for diagnosing whether collaboration is merely active or also conceptually productive, which aligns with the design challenge identified in inquiry research of ensuring that engagement is constructive rather than only procedural (de Jong et al., 2021). This triangulated evidence can guide iterative improvement of role design, scaffolding, and reflection prompts across repeated lesson implementations.

7.7. Limitations and Future Directions

Limitations

Although the three TEAC studies generate compelling evidence for the promise of technology-enhanced asymmetric collaboration, several methodological and contextual boundaries temper the strength and generalizability of the conclusions.

First, each investigation took place within a narrow cultural and curricular milieu: fifth–sixth graders in a public Estonian school for photosynthesis, seventh graders for an electricity unit, and ninth graders for a genetics module. Such contextual specificity constrains the degree to which these findings may hold in different national curricula or pedagogical traditions. While the underlying principles of structured role asymmetry, digital scaffolding, and reflection appear robust, their direct transferability to other educational systems must be established through further cross-cultural research.

Second, all TEAC implementations were delivered as single-lesson interventions without randomized control groups. This design precludes strong causal inference and leaves open questions about the persistence of collaborative-problem-solving (CPS) and metacognitive gains over time. Without longitudinal follow-up or multi-session designs, it is not possible to determine whether students retain improved inquiry skills or conceptual understanding beyond the immediate classroom episode.

Third, our reliance on student self-reports to gauge CPS dimensions introduces potential bias. Learners' metacognitive awareness and social desirability concerns may distort self-evaluations, and indeed several subscales in Study III (perspective-taking, social regulation, interdependence) showed poor internal consistency (α's ranging from –.10 to .36). These psychometric weaknesses warrant caution when interpreting fine-grained distinctions among collaborative skills.

Fourth, inquiry assessment focused substantially on specific competencies, including variable identification and structured reasoning within the designed tasks. While this is aligned with the intervention's design emphasis, it offers limited evidence about more expansive inquiry practices, such as iterative experimental redesign across extended inquiry sequences.

Fifth, although TEAC is theoretically grounded in CLT, no direct measures of cognitive load were collected. As a result, CLT claims are framed as design rationale and interpretive support rather than as empirically verified reductions in extraneous load (Kalyuga et al., 2003; Sweller, 1988, 2022). In addition, the work was conducted in face-to-face settings. The extent to which TEAC's assumptions about interaction richness and regulation generalize to remote or fully online collaboration remains an open question.

Sixth, the TEAC framework prioritizes task structure and interactional processes and therefore does not explicitly address individual personality characteristics or pre-existing social relations between partners, which may nevertheless influence how role asymmetry is enacted in practice.

Lastly, although teachers co-designed and facilitated each simulation, their perspectives on feasibility, technology integration challenges, and necessary supports were not systematically collected. This omission limits our understanding of the practical considerations required for wider adoption and sustainable implementation of the TEAC framework in everyday classroom practice.

Future Research

Building on the patterns and constraints revealed in this thesis, six priority avenues are identified for advancing the TEAC framework and deepening our collective understanding of technology-enhanced collaborative inquiry:

1. **Expanding Cross-Cultural and Disciplinary Contexts.**
   To overcome the limits of Estonian-only studies, subsequent work must introduce TEAC into a variety of educational systems, cultural settings, and

curricular domains. Embedding the framework in teacher-training programmes and national standards, rather than as an isolated DBR project, will test its robustness and reveal how local pedagogical traditions shape its efficacy. Applying TEAC to subjects beyond the life and physical sciences (e.g. earth science, engineering, mathematics) will further illuminate its adaptability to diverse inquiry contexts.

2. **Conducting Longitudinal DBR Cycles for Causal and Durable Effects**
   Moving beyond one-off lessons, future investigations should adopt longitudinal DBR designs, tracking the same cohorts across multiple units or over an academic year. Such studies are essential to establish stronger causal claims about TEAC's impact on Collaborative Problem Solving and metacognitive regulation, as well as to assess whether initial gains endure, transfer to novel tasks, and consolidate into classroom norms.

3. **Triangulating and Refining Collaborative Assessment**
   To address self-report biases and low reliability in certain subscales, forthcoming research must blend student questionnaires with peer ratings, systematic behavioural observations, and analysis of digital interaction logs. Refinement of the CPS instrument, by increasing item counts per dimension and integrating psychometrically validated scales, will strengthen construct validity and resolve discrepancies among subjective and objective indicators of collaboration.

4. **Broadening and Automating Inquiry Measures**
   Current assessments privilege variable-identification tasks at the expense of richer, process-oriented experimentation behaviours. Future work should develop more holistic inquiry tasks, requiring hypothesis revision, experimental design, data interpretation, and argumentation, and couple them with automated process-data analyses (e.g. sequence mining of student actions) to capture the full trajectory of students' procedural fluency and reasoning strategies.

5. **Validating Cognitive-Load Mechanisms with Objective Metrics**
   The design priorities of TEAC rest on CLT, yet direct empirical evidence is lacking. Incorporating eye-tracking, pupillometry, or other physiological sensors into TEAC studies will allow researchers to observe learners' mental effort in real time, thereby substantiating or refining CLT-based design claims and revealing which scaffolds most effectively manage intrinsic, extraneous, and germane load.

6. **Systematically Engaging Educators in Iterative Co-Design**
   Finally, practitioners' voices must become a formal element of future DBR cycles. By enlisting teachers in structured co-design workshops and capturing their reflections through interviews and implementation logs, researchers can

surface practical constraints, pedagogical adaptations, and strategies for fostering teacher ownership. This systematic collaboration will ensure that TEAC evolves in tandem with the needs and expertise of those who enact it daily.

Pursuing these research directions will not only address the limitations identified in this thesis but also chart a pathway towards scalable, evidence-informed models of technology-enhanced collaborative inquiry that can thrive across diverse classrooms and cultures.

SUMMARY IN ESTONIAN

Digitehnoloogiate abil toetatud asümmeetrilise koostöise uurimusliku õppe kavandamine loodusainetes

Kaasaegne loodusteaduslik haridus seisab silmitsi väljakutsega kujundada õpilastes lisaks aineteadmistele ka võimekust lahendada keerukaid probleeme koostöös teistega (Griffin & Care, 2015; OECD, 2017). Kuigi koostöine õpe ja digitehnoloogiate kasutamine on õppekavades kõrgelt väärtustatud, ei taga nende mehhaaniline rakendamine automaatselt sügavat õppimist **(**Burns jt, 2024; Chai jt, 2024; de Jong jt, 2021; Lazonder & Harmsen, 2016; OECD, 2013). Praktikas võib koostöö jääda pealiskaudseks (Barron, 2005; Premo jt, 2022), rühmaliikmete panus ebaühtlaseks (Andrews-Todd jt, 2022; Burns jt, 2024) ning uurimuslik mõistmine puudulikuks (Hofstein & Lunetta, 2004; Mayer, 2004). Käesolev doktoritöö lähtub eeldusest, et koostöise probleemilahendusoskuse (KPLO) areng eeldab teadlikult kavandatud pedagoogilist disaini, mis integreerib süsteemselt koostöö, uurimusliku tegevuse ja refleksiooni.

Doktoritöös kavandatakse, rakendatakse ja empiiriliselt uuritakse tehnoloogiaga toetatud asümmeetrilise koostöö (Technology-Enhanced Asymmetric Collaboration, TEAC) raamistikku kui pedagoogilist disaini koostöise uurimusliku õppe toetamiseks autentsetes loodusteaduslikes klassiruumides. Raamistiku eesmärk on toetada õpilaste aineteadmiste ja uurimuslike teadmiste kujunemist ning koostöise probleemilahendusoskuse arengut (toetudes mudelitele: Hesse jt, 2015; Van den Bossche jt, 2006), käsitledes õppimist kolme omavahel seotud „õppimise hammasratta“ kaudu: teadmiste konstrueerimine, koostöine interaktsioon ja metakognitiivne regulatsioon refleksiooni kaudu. Töö keskne tees on, et sügav ja kestlik õppimine digitaalses koostöökeskkonnas tekib vaid siis, kui need tasandid on õpikeskkonnas teadlikult kooskõlastatud.

TEAC-raamistiku potentsiaali uurimiseks juhindus töö kolmest põhilisest uurimisküsimusest, mis struktureerisid kolmefaasilise disainipõhise uurimuse (Design-Based Research, DBR). Iga uurimisfaas keskendus erinevale digitaalsele simulatsioonikeskkonnale (fotosüntees, elekter ja geneetika) ning võimaldas raamistikku iteratiivselt täpsustada vastavalt eelnevates etappides ilmnenud disainiväljakutsetele.

Uurimisküsimus 1: Rühma struktuur

Kuidas mõjutab rühma suurus õpilaste uurimuslikku sooritust ja koostöödünaamikat tehnoloogiaga toetatud asümmeetrilistes simulatsiooniülesannetes?

Rühma suuruse analüüs toimis TEAC-raamistiku väljatöötamisel disainilise eeltingimusena, mille eesmärk oli määratleda optimaalne rühma struktuur enne rolliasümmeetria süstemaatilist rakendamist. See uurimisküsimus oli keskne I faasis (fotosünteesi uuring), kus kõrvutati kahe- ja neljaliikmeliste rühmade tööd, et selgitada rühma suuruse mõju osalusele, vastutuse jaotusele, tegevuste

koordineerimisele ning uurimusliku koostöö tulemuslikkusele. Analüüs võimaldas hinnata, millises rühmas on asümmeetrilise digitaalse koostöö rakendamine pedagoogiliselt kõige otstarbekam (Kalyuga jt, 2003; Sweller, 1988).

Uurimisküsimus 2: Koostöine interaktsioon

Kuidas mõjutab struktureeritud rolliasümmeetria õpilaste võimet teadmisi ühiselt konstrueerida ja probleeme koostöiselt lahendada?

See uurimisküsimus läbib kõiki kolme uurimisfaasi ning moodustab TEAC-raamistiku keskse disainipõhimõtte. II faasis (elekter) ja III faasis (geneetika) täpsustati ja laiendati rollijaotusi uutes ainevaldkondades ja tehnoloogilistes keskkondades, et analüüsida nende mõju dialoogile, läbirääkimistele ja vastastikusele toetusele koostöise probleemilahenduse käigus. Tulemused näitasid, et kuigi rolliasümmeetria suurendas osalust ja lõi positiivse vastastikuse sõltuvuse (Johnson & Johnson, 1999), ei taganud koostöine interaktsioon iseenesest sügavat uurimuslikku mõistmist (Kozlov & Große, 2016).

Uurimisküsimus 3: Regulatsioon refleksiooni kaudu

Kuidas toetavad reflektiivsed praktikad ja digitaalsed juhised õpilaste metakognitiivset regulatsiooni koostöise uurimusliku tegevuse käigus?

Kolmas uurimisküsimus käsitles refleksiooni kui metakognitiivse regulatsiooni mehhanismi ning arenes järkjärguliselt süveneva disainiloogikana. I faasis piirduti kaudsete ja ülesandejärgsete aruteludega, II faasis rakendati struktureeritumaid refleksioonivorme ning III faasis kujunes välja terviklik RRL-refleksiooniprotokoll (Remember–Recall–Learning). Reflektiivsed praktikad aitasid õppijatel teadvustada oma arusaamu, hinnata koostöö kvaliteeti ning seostada tegevust õpitulemustega, toetades eeskätt aineteadmiste kinnistumist, kuid ka KPLO arengut osalemise, perspektiivivõtu ja sotsiaalse regulatsiooni tasandil (Järvelä jt, 2016).

Igas disainipõhise uurimuse tsüklis kasutati segameetodilist lähenemist (Barab & Squire, 2004; Creswell & Plano Clark, 2018), kombineerides kvantitatiivseid andmeid (rubriigipõhiselt hinnatud õpitulemused ning ATC21S-raamistikul põhinevad koostöise probleemilahendusoskuse küsimustikud) ja kvalitatiivseid allikaid (struktureeritud refleksioonid ning õpetaja juhitud arutelud). Andmekogumise ja analüüsi vahendid täpsustusid iteratsioonide jooksul, tagades, et TEAC-raamistik kujunes ühtaegu teoreetiliselt põhjendatuks ja praktilisele klassiruumikontekstile sobivaks.

Doktoritöö keskne järeldus on, et koostöine interaktsioon ei võrdu automaatselt koostöise probleemilahendusoskuse arenguga. Asümmeetriline rollijaotus toimib küll koostöö katalüsaatorina, kuid sügavam õppimine eeldab reflektiivset ja metakognitiivset tuge, mis aitab õppijatel oma tegevust ja koostööd teadlikult reguleerida. TEAC-raamistik näitab, kuidas digitaalseid simulatsioone, rollijaotust ja refleksiooni saab klassiruumis süsteemselt lõimida, et toetada õppimise kognitiivseid, sotsiaalseid ja regulatiivseid protsesse.

Kokkuvõttes pakub käesolev doktoritöö teaduspõhiseid ja praktiliselt rakendatavaid disainipõhimõtteid õpetajatele, õpetajakoolitajatele ja haridusteadlastele, kes soovivad toetada koostöise probleemilahendusoskuse ja uurimuslike teadmiste arengut loodusteaduslikus hariduses. Töö rõhutab, et tõhus digitaalne koostöö ei teki iseenesest, vaid nõuab õpikeskkonna teadlikku kujundamist, kus tehnoloogia toetab õppijatevahelist vastastikust sõltuvust, mõtestatud dialoogi ja refleksiooni.

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ORIGINAL PUBLICATIONS

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Professional Employment

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The development of teacher education competence at the Pedagogicum of the University of Tartu.

Publications

Rannastu-Avalos, M., Siiman, L., & Mäeots, M. (2025). Understanding collaborative problem-solving with smartphone-based asymmetric simulations in an authentic inquiry science lesson. *Journal of Baltic Science Education*, *24*(4), https://doi.org/10.33225/jbse/25.24.684

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Publikatsioonid

Rannastu-Avalos, M., Siiman, L., & Mäeots, M. (2025). Understanding collaborative problem-solving with smartphone-based asymmetric simulations in an authentic inquiry science lesson. *Journal of Baltic Science Education*, *24*(4), https://doi.org/10.33225/jbse/25.24.684

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