



UNDERSTANDING COLLABORATIVE PROBLEM- SOLVING WITH SMARTPHONE- BASED ASYMMETRIC SIMULATIONS IN AN AUTHENTIC INQUIRY SCIENCE LESSON

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Abstract. Collaborative problem-solving (CPS) is increasingly essential in both scientific practice and modern education, yet remains difficult to embed authentically in classrooms. This study addressed that gap by integrating CPS into a ninth-grade biology lesson using a smartphone-based asymmetric simulation. The innovative three-phase instructional scenario, which combined preparation, hands-on simulation, and guided reflection, was implemented in a real classroom setting with 43 students. Data from worksheets, reflective responses, and a CPS self-evaluation tool revealed high levels of student engagement and strong social-regulation skills, yet also pointed to challenges in applying inquiry strategies and fostering mutual interdependence. Rather than offering conclusive claims, this study positioned itself as a pilot exploration of how digital asymmetry can trigger authentic collaboration in science learning. The findings illuminate both the potential and the pedagogical tensions of using mobile-supported tools to support 21st-century skills in inquiry-based education.

Keywords: collaborative problem-solving, inquiry-based learning, science education, technology-enhanced learning

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Introduction

Collaborative problem-solving (CPS) is increasingly recognized as a core competency for 21st-century education, as evidenced by international frameworks such as ATC21S (Griffin & Care, 2014) and PISA (OECD, 2017). However, integration of CPS into school curricula remains limited in many contexts (Graesser et al., 2018). For example, in Estonia, while the national curriculum emphasizes inquiry-based learning (IBL) and digital technologies, few studies have examined how CPS skills are fostered and evaluated in science classrooms, especially using simulation-based approaches. Previous research by Mäeots and Pedaste (2014) and Rannastu et al. (2019) has explored technology-enhanced inquiry, but without a specific focus on collaborative skill development.

Advancements in digital technologies offer new possibilities for addressing this gap. Tools such as computer simulations and smartphone-based learning applications can support engaging, interactive environments that bridge the gap between theoretical knowledge and real-world application (Chen & Tsai, 2021; De Jong et al., 2021). In particular, asymmetrical simulations (where learners are assigned different roles or access to different information) have shown promise in promoting collaboration and engagement in science education, especially in physics (Rannastu et al., 2019; Rannastu-Avalos et al., 2023). However, the effectiveness of such approaches across various science domains, including biology, still requires further exploration.

Biology education presents unique challenges due to the abstract nature of many of its core concepts, which students often struggle to apply in practical or real-world contexts. This challenge offers a valuable opportunity to examine collaborative, technology-enhanced learning methods that can support deeper conceptual understanding. Recent studies have highlighted that integrating digital tools, such as simulations, interactive videos, and adaptive platforms, not only helps visualize complex biological processes but also enhances engagement, personalization, and collaboration (Cartono, 2022; Zhou & Lewis, 2021). These insights suggest that well-designed technological



interventions can help address the specific challenges of biology education while supporting the broader goals of CPS development, IBL, and 21st-century skill acquisition.

Theoretical Framework

The theoretical framework of this study draws on three core strands: (1) CPS, as conceptualized by Hesse et al. (2014) and Griffin and Care (2014); (2) IBL (Pedaste et al., 2015); and (3) digital technologies in education (Pea, 1993; Stahl et al., 2005). CPS is treated as a multifaceted construct encompassing individual cognitive processes and social interaction. Inquiry-based approaches are positioned as a pedagogical structure for promoting CPS, while digital technologies are considered both as mediators and scaffolds for collaboration in science education contexts.

A recent systematic review (Agustin et al., 2024) reinforced the educational potential of virtual biology laboratories, particularly in settings with limited access to physical lab infrastructure. The findings of the review emphasized that the success of such environments depended not only on technological capabilities but also on pedagogical design, including scaffolds like feedback and structured tasks. This aligns with the theoretical framing adopted in this study, in which simulations are seen as socio-cognitive tools that support collaborative inquiry and regulation. Moreover, their emphasis on supporting abstract and microscopic biological content parallels the visual scaffolding goals embedded in the simulations used in this study. Finally, their review highlights that most effective virtual labs adopt inquiry-based and problem-based learning models, which further supports the integration of CPS frameworks and asymmetric task structures implemented in the current research.

Chen et al. (2023) examined the educational affordances of the Go-Lab online platform for supporting IBL in Taiwanese secondary schools. The study emphasized the role of collectivist orientations and computer self-efficacy in shaping students' collaborative and self-directed inquiry. Their use of simulations to teach abstract genetics concepts complements the focus on visual scaffolding for complex biological phenomena in this study, reinforcing the pedagogical rationale behind the smartphone-based, asymmetrical simulation. Notably, their inclusion of a rabbit genetics simulation mirrors the design used here, further validating the relevance of simulation-based approaches in supporting abstract concept learning within digitally mediated collaborative science tasks. This aligns with Siiman and Halchevska (2023), who implemented asymmetric simulations, such as the Collaborative Rabbit Genetics Lab and the Seesaw Lab, to create interdependence between students. Their study reinforced that such designs, in which students hold different parts of the solution, mirror real-world teamwork and require coordinated problem-solving, communication, and mutual dependence. These findings provide additional theoretical grounding for the emphasis on distributed roles and technology-supported collaboration adopted in this study within the context of science education.

Collaborative Problem-Solving Skills

CPS is a multifaceted 21st-century skill that integrates individual cognitive processes with social interaction (Graesser et al., 2018; Hesse et al., 2014). It is widely recognized in both educational research and international assessments such as the ATC21S project (Griffin & Care, 2014) and PISA (OECD, 2017), which conceptualize CPS as essential for navigating complex, real-world challenges. The ATC21S framework emphasizes five cognitive-social skills: participation, perspective-taking, social regulation, task regulation, and knowledge building (Hesse et al., 2014). Meanwhile, the PISA framework highlights three collaborative processes: establishing shared understanding, managing team organization, and taking coordinated action (OECD, 2017). These models underscore the dual importance of teamwork (interpersonal coordination) and taskwork (problem analysis and decision-making) in CPS (Salas et al., 2015).

In the study, these frameworks informed both the educational design and the CPS skills questionnaire, which assessed students' self-perceived development in participation, perspective-taking, and social regulation. These skills were chosen for their relevance to adolescent learners and their alignment with the ATC21S framework.

Fostering positive interdependence, a key mechanism of effective collaboration (Johnson & Johnson, 1999), was a primary goal of the simulation activity, which was designed with asymmetry: each partner had access to different controls and information, making collaboration essential. This structure required students to engage in shared reasoning, coordinate strategies, and regulate interaction in order to complete the task successfully. In doing so, the design aimed not only to support content learning but also to develop core social-cognitive components of CPS.



IBL and CPS in Science Education

IBL is a pedagogical approach that engages students in active knowledge construction through questioning, investigation, and reasoning, which are core components of science education. It aligns closely with constructivist theories of learning (Dewey, 1986; Piaget, 1976) and is particularly relevant for developing CPS skills. Research indicates that IBL improves subject-specific understanding and inquiry skills (Lazonder & Harmsen, 2016; Mäeots & Pedaste, 2014) while also fostering communication and group reasoning through collaborative inquiry (Zhu et al., 2019).

One key intersection between IBL and CPS is the control-of-variables strategy (CVS), which refers to the ability to design fair tests by manipulating and isolating variables (Schwichow et al., 2016). This was operationalized in the simulation-based biology task used in this study, in which students were required to identify independent and dependent variables as part of solving a collaborative genetics problem. Because of the asymmetrical nature of the simulation, successful problem-solving required coordinated experimentation and communication between students, reinforcing both cognitive and social elements of CPS.

Recent studies continue to validate the relevance of IBL as a central pedagogical model in digital science education. Meng and Jumaat (2024) demonstrated that an online IBL environment significantly improved secondary students' behavioral engagement and science performance. Their quasi-experimental study revealed that the experimental group using simulation-based, structured inquiry tasks designed within the Go-Lab and NOBOOK platforms demonstrated greater persistence, on-task behavior, and self-regulation compared to the control group. These findings reinforce the importance of integrating digital technologies with student-centered pedagogies, aligning with Pea's (1993) view of technology as a cognitive and social scaffold and supporting the use of smartphone-based simulations in this study to enhance collaborative inquiry and learning outcomes.

However, implementing collaborative IBL in authentic classrooms presents pedagogical challenges. Teachers must balance guidance with autonomy, particularly when integrating digital technologies and complex simulations. In this study, these challenges were addressed through guided scaffolding, including worksheet prompts that structured student interaction and subsequent reflection activities. This structured support was essential for helping students manage the dual demands of inquiry and collaboration (Hmelo-Silver et al., 2007), especially in the context of technology-enhanced biology learning.

Reflective Practices in CPS

Reflection plays a vital role in the development of CPS skills, particularly in inquiry-based science education. Guided reflection was incorporated in this study to enhance students' metacognitive and socio-metacognitive awareness, drawing on Schön's (2017) concepts of reflection-in-action and reflection-on-action, as well as Kolb's (1984) experiential learning cycle. In collaborative settings, this form of reflection supports group regulation processes such as negotiating roles, resolving conflict, and evaluating progress (Järvelä et al., 2016). Reflection was embedded in the lesson design through two key components: post-simulation reflection questions, which prompted students to evaluate the correctness of their responses and analyze the success or failure of their collaboration; and a teacher-facilitated class discussion, which encouraged students to articulate and examine their collaborative experiences. These practices aimed to help students make sense of their inquiry processes and peer interactions, facilitating deeper conceptual understanding and the transfer of CPS skills to new contexts (Furberg, 2009; Perkins & Salomon, 1989). Grounding reflection in both theory and practical implementation underscores its significance not only for individual learning but also for fostering shared understanding in collaborative environments.

Digital Technologies and CPS

Digital technologies play a pivotal role in enhancing CPS, both by supporting social interaction and facilitating cognitive processes (Pea, 1993; Stahl et al., 2005). Research in computer-supported collaborative learning (CSCL) has shown that digital technologies can enhance communication, provide shared workspaces for co-construction of knowledge, and offer dynamic visualizations that scaffold complex problem-solving tasks (De Jong et al., 2023; Stahl et al., 2005; Wise & Schwarz, 2017). These affordances are particularly valuable in science education, where simulations and virtual labs have been shown to promote inquiry skills and conceptual understanding (Olympiou & Zacharia, 2013).



Recent research further validates the use of animation-based inquiry environments. For example, Sui et al. (2023) demonstrated that animated simulations, such as their “Methane Mystery” task, can elicit diverse student inquiry profiles and effectively support the development of data analytics, control of variables, and scientific reasoning skills. The use of animation-based tasks in their study shares conceptual similarities with the virtual simulations employed in this research; both approaches provide structured, dynamic environments that support students in observing cause-effect relationships, testing hypotheses, and engaging in reflective reasoning. This growing body of evidence reinforces the educational validity of using virtual or animated simulations to support CPS and inquiry-based science learning.

This study extended previous work by integrating smartphone-based asymmetrical simulations into a ninth-grade biology lesson. The simulations were designed to require coordinated interaction, with each student controlling a different subset of variables, thus necessitating communication and shared decision-making. This design encouraged positive interdependence and mirrored real-world collaborative scientific inquiry. Moreover, the use of familiar, portable devices supported flexibility in classroom integration, addressing both the technical and pedagogical challenges highlighted by Bell et al. (2009) and Kirschner et al. (2006).

Importantly, scaffolding mechanisms were incorporated within the digital environment, including structured worksheets, reflection questions, and teacher guidance, to manage cognitive load and support productive collaboration, as recommended by Kaldaras et al. (2024). These elements align with the broader theoretical framework that sees digital technologies not only as facilitators but also as scaffolds for interaction, reasoning, and regulation within collaborative learning environments. These findings contribute to a nuanced understanding of how smart technologies can be used intentionally to support both the social and cognitive dimensions of CPS in subject-specific science education.

Research Problem

Despite the acknowledged importance of CPS, its integration into school classrooms, particularly in science education, remains a challenge. Care and Kim (2017) highlighted that CPS is still rarely integrated into regular classroom instruction. Building on this concept, the challenge can be understood as providing effective learning experiences that integrate subject knowledge, inquiry skills, and CPS within a regular classroom setting. In Estonia, while the national curriculum emphasizes IBL and collaboration, these skills are rarely assessed or supported through structured classroom technologies. Few studies have examined how CPS can be meaningfully integrated into regular science lessons using digital technologies. This study addressed this gap by exploring how an asymmetrical, smartphone-based simulation might support CPS in a real classroom setting.

Research Aim and Research Questions

This study aimed to design and implement an inquiry-based biology lesson that integrated CPS skills through an asymmetrical smartphone-based simulation. The goal was to foster students’ subject-specific knowledge, inquiry skills, and CPS skills. The lesson was grounded in established CPS frameworks (Griffin & Care, 2014; Hesse et al., 2014) and built on previous work in technology-enhanced collaborative learning (Rannastu-Avalos et al., 2023). The influence of the integrated approach on student learning and collaboration was explored through three research questions that guided the study.

1. How does a collaborative asymmetrical simulation activity related to the biology topic of genetics impact students’ subject knowledge acquisition and inquiry skill performance?
2. How do students perceive the impact of collaboration on their task performance?
3. How do students evaluate their CPS skills after engaging in the asymmetrical simulation activity?

This study responds to both national curricular goals and international priorities by exploring how CPS and IBL can be effectively integrated into authentic science classroom contexts using digital tools. Although situated within an Estonian secondary school, the study offers insights that are transferable to other educational systems seeking to embed 21st-century skills into everyday classroom practice. Through the implementation of an asymmetrical, smartphone-based simulation, the research demonstrates how technology-enhanced environments can foster both content mastery and collaborative engagement within a single inquiry task. The study provides

practical evidence on how such tools support role distribution, peer coordination, and student reflection, which are critical factors for successful CPS integration in science education.

Research Methodology

Design and Implementation

To examine how CPS skills can be fostered and evaluated through IBL and digital technologies, this study employed a mixed-methods study design situated within a ninth-grade biology classroom in Estonia. The research was conducted in 2023 and was guided by theoretical frameworks related to CPS (Griffin & Care, 2014; Hesse et al., 2014), IBL (Pedaste et al., 2015), and digital learning environments (Stahl et al., 2005). By integrating quantitative and qualitative methods, the study aimed to capture how students' subject knowledge, inquiry skills, and collaborative behaviors evolved through participation in a smartphone-based, asymmetrical simulation.

The lesson design followed a three-phase prototype learning scenario, co-developed with the classroom teacher to align with the Estonian national curriculum (Ministry of Education and Research, n.d.) and inquiry-based pedagogy (Pedaste et al., 2015). In Phase 1, students were introduced to the topic and prepared for the collaborative activity. In Phase 2, they worked in pairs or triads using asymmetrical smartphone simulations to complete a worksheet that required applying biology knowledge and inquiry strategies. In Phase 3, students reflected on their performance and collaborative experience through a teacher-led class discussion and then completed a post-activity questionnaire. This structured sequence was designed to integrate inquiry, technology, and reflection in support of CPS development.

Participants

The study involved 43 ninth-grade students (53% girls, 47% boys; mean age 15.7 years, $SD = .34$) from two classes at a secondary school in Estonia. This number reflects all students who were present and participated in the lesson on the day of the activity. Students were randomly assigned to 17 pairs and three groups of three, depending on availability and class size constraints.

The activity was conducted as part of the school's regular curriculum and followed institutional and national ethical guidelines for educational research. Students were informed about the voluntary nature of participation, their right to withdraw, and how their data would be anonymized. Passive consent was obtained via a school-approved protocol, and an alternative non-digital activity was provided for any students who chose not to participate.

Asymmetrical Simulation

A smartphone-based simulation focusing on rabbit genetics was used to support collaboration through an asymmetrical task design. Each student in a pair accessed the same simulation environment (the Collaborative Rabbit Genetics Lab) but interacted with it through different entry points that offered distinct control features. Student A could manipulate the ear shape (straight or floppy) of rabbits with black fur, while Student B controlled ear shape traits for rabbits with white fur. This division of control required verbal communication and joint reasoning, ensuring that successful task completion was dependent on interdependent problem-solving.

This design promotes positive interdependence and mirrors real-world collaborative scientific problem-solving, where scientists often bring complementary expertise to shared inquiries. The simulation is freely accessible at <https://leosiiman.neocities.org/simulations> and can be translated into various languages for diverse classroom contexts.

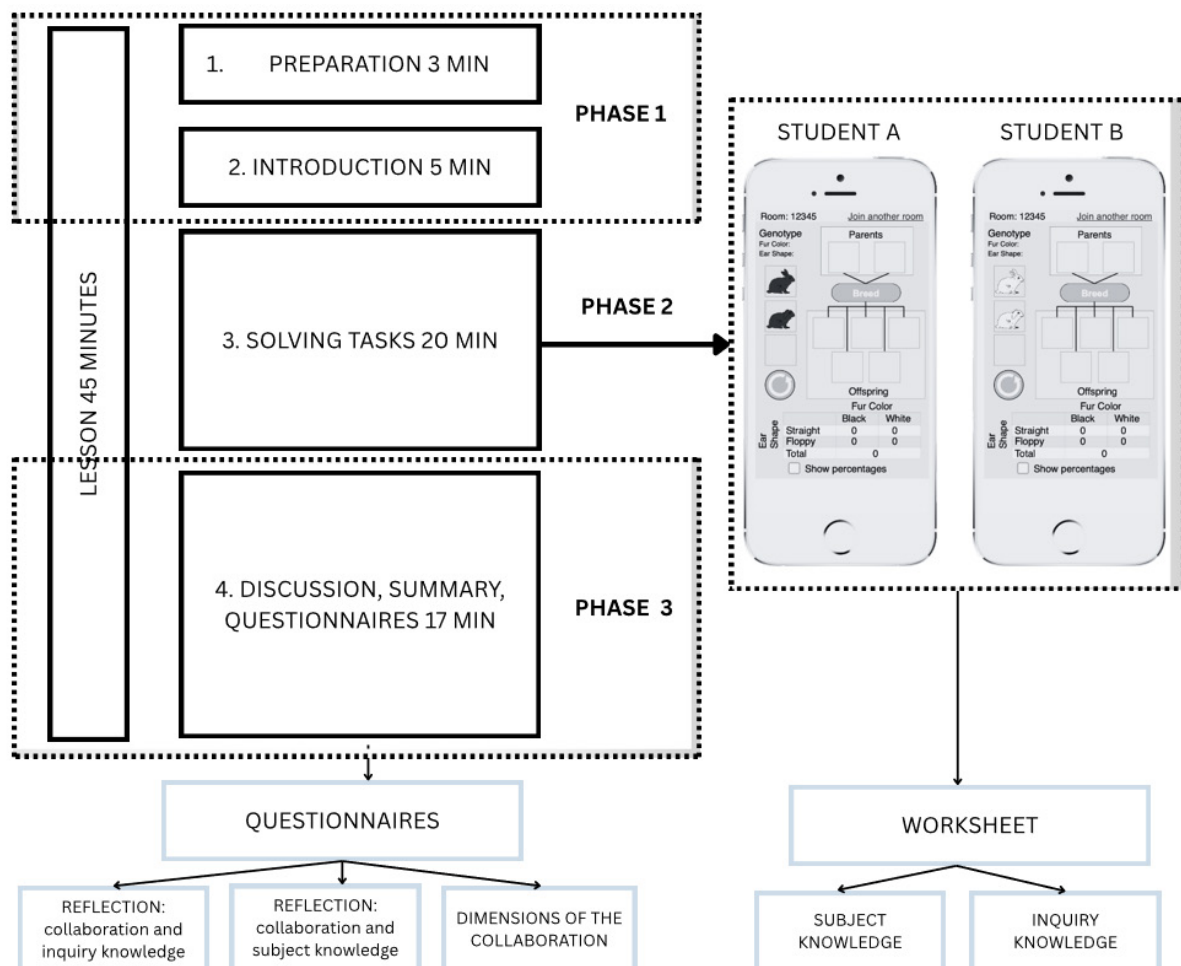
The same simulation was also used in an online context by Siiman and Halchevska (2023) with Ukrainian students during the Russian invasion. Their study validated the simulation's capacity to trigger inquiry and collaboration through interdependent role structures, reinforcing its appropriateness for assessing CPS. Their findings also highlight the potential of such designs to scaffold coordination and shared understanding in distributed learning environments.



Instruments and Materials

Three primary instruments were developed and used to examine CPS skills in biology (see Table 1 and Figure 1):

1. Individual Worksheet Questions: A structured worksheet with three questions assessing subject knowledge and inquiry skills in biology. The design ensured that students could not find answers independently, thus encouraging collaboration.
2. Reflection Questions: Open-ended questions prompting students to evaluate their performance, explain collaboration benefits, and reflect on challenges.
3. CPS Skills Questionnaire: A 10-item, 5-point Likert-scale questionnaire assessing four dimensions of CPS skills: participation, perspective-taking, social regulation, and interdependence.

Figure 1*The Research Design and Phases*

Note. Students are introduced to the topic in the first phase, collaborate using asymmetric smartphone simulations in the second phase, and reflect on their performance and collaboration in the third phase.

Data Collection and Analysis

Data for this study were collected from three primary sources: student worksheets completed during the collaborative simulation activity, the post-activity Collaborative Problem-Solving (CPS) Skills Questionnaire, and students' written reflections. A mixed-methods approach was employed, combining quantitative scoring of content and inquiry-based knowledge with qualitative analysis of students' self-evaluations and perceived collaboration dynamics.

To evaluate students' disciplinary and inquiry performance, worksheet responses were assessed across three dimensions: K1 (first subject knowledge item), K2 (second subject knowledge item), and K3 (inquiry knowledge item). All responses were rated using a three-point scale based on scientific accuracy, conceptual clarity, and completeness. A score of 3 (high level) indicated a well-developed and fully justified response grounded in relevant science concepts. For example, a high-level K1 response stated: "If both black rabbit parents have genotype Aa , then 25% of their offspring can be white with genotype aa ," demonstrating understanding of Mendelian inheritance.

A score of 2 (average level) indicated partial understanding with minor errors or omissions. An example of an average K2 response was: "White color is recessive and could come from grandparents," which recognizes inheritance but does not fully apply simulation-based reasoning. A score of 1 (low level) was assigned to vague or incorrect answers, such as "Because one parent is white," which lacks genetic reasoning.

The same criteria were used for K3 (inquiry knowledge), which required students to identify either independent or dependent variables based on the version of the worksheet. High-level responses correctly named variables that students could manipulate or measure in the simulation. For instance, a student who responded, "Independent variables: ear shape and fur color of the parents," demonstrated a correct understanding of experimental structure. Average responses often identified relevant features but were phrased unclearly or mixed variable types. For example, "Color and ears are different for each rabbit," was coded as average due to lack of clarity. Low-level answers were typically off-topic or identified outcomes as independent variables (e.g., "The babies are the variable"), indicating confusion about inquiry design. The scoring rubric was applied consistently across both worksheet versions (A and B), allowing comparison of students' grasp of subject matter and inquiry reasoning.

In addition to assessing performance, students' metacognitive evaluations were analyzed using three reflection indicators: Remember, Recall, and Learning. The *Remember* score assessed whether students accurately reproduced what they had initially written on the worksheet. A score of 2 indicated accurate recall (*Full answer*), 1 represented a partial or vague recollection (*Incomplete answer*), and 0 was given when the recalled answer was incorrect (*Wrong answer*). An additional *No answer* category was used for blank responses. For example, a student who initially wrote " $Aa \times Aa$ gives 25% white" and later reflected "We said $Aa \times Aa$; that gives 25% white" received a 2. Another who wrote "I think it had something to do with recessive genes" was scored 1, and a student who recalled "I said both were white" when the original had no genotype reference received 0.

Recall scores captured students' metacognitive accuracy, indicating whether they correctly judged their original answer as right or wrong. A score of 3 indicated correct metacognitive awareness, 1 reflected a mismatch between judgment and actual correctness, and 0 was assigned when no such judgment was provided.

The *Learning* indicator reflected conceptual development across the task and reflection phases. Students received a score of 1 (*Visible learning*) if they correctly answered in both phases or corrected an earlier mistake during reflection. A score of 0 (*Not visible*) indicated that the student's response lacked evidence of learning.

These indicators were coded separately for each knowledge dimension and then aggregated for reporting. Table 2 in the Results section summarizes the proportion of students performing at high, average, and low levels in each domain, as well as their reflection outcomes (Remember, Recall, and Learning).

Reliability and Validity

Multiple strategies were employed to ensure the reliability and validity of the study. The development of instruments was informed by well-established frameworks for collaborative problem-solving (Griffin & Care, 2014; Hesse et al., 2014), and methodological rigor was supported through triangulation, researcher collaboration, and iterative coding of qualitative responses. The study adhered to reliability principles outlined by Williams and Morrow (2009), including independent coding, consensus-building sessions, and validation of coding across the research team.

Table 1
Assessed Activities and Their Examples

Research Question	Variable	Content
RQ1	Subject knowledge (K1)	Question 1: <i>In this computer model, black rabbits can give birth to a white offspring. How is it possible? Justify.</i>
	Subject knowledge (K2)	Question 2: <i>Explain what characteristics the two white rabbits in this simulation should have so that there is an equal probability (50%) that they will give birth to an offspring with flat ears or with pricked ears.</i>
	Inquiry knowledge (K3)	Question 3, version A: <i>List all the independent variables in this simulation.</i> Question 2, version B: <i>List all the dependent variables in this simulation.</i>
RQ2	Reflection on subject knowledge and collaboration (R1)	Question 1: <i>Were your responses to the worksheet questions 1 and 2 correct or incorrect? If correct, then how did collaboration help you be successful? If incorrect, why was your collaboration unsuccessful?</i>
	Reflection on inquiry knowledge and collaboration (R2)	Question 2: <i>Were your responses to the worksheet question 3 correct or incorrect? If correct, then how did collaboration help you be successful? If incorrect, why was your collaboration unsuccessful?</i>
RQ3	CPS skills	
	Participation ¹	
	Partic1	<i>I made an effort to solve the task while working collaboratively.</i>
	Partic2	<i>I was active when solving the task with my partner.</i>
	Partic3	<i>I was passive when solving the task with my partner.</i>
	Perspective-taking ¹	
	PeTa1	<i>I changed my opinion when my partner brought up new ideas.</i>
	PeTa2	<i>When my partner misunderstood me, I clarified my thoughts.</i>
	Social regulation ¹	
	SoReg1	<i>I took into account that my partner might have different collaboration skills than I do.</i>
	SoReg2	<i>When I had a disagreement with my partner, I tried to find solutions.</i>
	Interdependence ²	
	InterDep1	<i>My partner could not solve the task without my help.</i>
	InterDep2	<i>I could not solve the task without my partner's help.</i>
	InterDep3	<i>When my partner succeeded in their task, it had a positive impact on me.</i>

¹ From CPS skills of collaboration, Hesse et al. (2014)² From Van den Bossche et al. (2006), adapted Note. See also Figure 1.

One of the key instruments used was the CPS Skills Questionnaire, which consisted of 10 Likert-scale items adapted from the ATC21S framework. Responses were rated on a 5-point scale (1 = strongly disagree to 5 = strongly agree), allowing students to self-assess their collaborative behavior. The items were distributed across four theoretically grounded dimensions of collaborative problem-solving: participation (3 items), perspective-taking (2 items), social regulation (2 items), and interdependence (3 items). One negatively worded item in the participation subscale (Partic3_p) was reverse-coded to ensure that higher scores consistently reflected stronger CPS performance.

Internal consistency was assessed using Cronbach's alpha (JASP version 0.18.3). The participation subscale demonstrated acceptable reliability ($\alpha = .779$), while the perspective-taking ($\alpha = .141$), social regulation ($\alpha = -.101$), and interdependence ($\alpha = .359$) subscales showed low or negative alpha values, indicating weak internal consistency within those dimensions. When all 10 items were combined into a single scale, the overall reliability improved to an acceptable level ($\alpha = .668$), justifying the use of a total CPS index in the analyses.

Given the limited sample size ($N = 43$), interpretations of subscale reliability coefficients should be approached with caution. These limitations were taken into account in the interpretation of the findings and are discussed further in the relevant sections of this study.



Research Results

Student Performance in Subject Knowledge and Inquiry Skills

Student performance in subject knowledge and inquiry skills varied throughout the collaborative simulation activity. The analysis focused on two indicators: subject knowledge (K1, K2) and inquiry knowledge (K3), revealing a multifaceted picture of learning outcomes. While many students demonstrated strong theoretical understanding, their ability to apply inquiry strategies was more inconsistent, suggesting differentiated levels of content acquisition and inquiry skill performance.

Subject Knowledge (K1 and K2)

Students' responses to the first content-related question (K1), which asked them to explain how black rabbits could produce white offspring, revealed strong conceptual understanding (Table 2). A high-level answer (score = 3) was exemplified by a student who explained, "If both black rabbit parents have genotype Aa, then 25% of their offspring may be white with genotype aa." This demonstrated accurate use of genetics terminology and understanding of recessive inheritance.

An average-level response (score = 2) included statements like, "White color is recessive and could come from grandparents," indicating partial grasp of genetic principles but lacking precise explanation. A low-level response (score = 1), such as "Because one parent is white," was vague and unsupported by evidence from the simulation.

In total, 81% of students reached the high level, while only 12% provided average-level answers, and 7% gave low-level responses. These results were supported by the reflection data: 79% accurately remembered their answer (Remember = 2), 74% correctly judged whether their answer had been right or wrong (Recall = 3), and 77% showed visible learning (Learning = 1), meaning they either maintained a correct answer or improved upon a previously incorrect one.

In contrast, student responses to the second subject knowledge question (K2), which focused on identifying the parental genotypes required to produce offspring with a 50% probability of having different ear types, were more varied. High-level responses (score = 3) accurately identified the necessary genotypes, for example: "One rabbit must be Bb and the other bb to give a 50% chance of floppy or straight ears." Average-level answers (score = 2) reflected partial accuracy, such as "They need different genes, one dominant and one recessive," while low-level answers (score = 1) often made assumptions without using genetic terminology, e.g., "Because one rabbit had floppy ears."

Only 42% of students scored at the high level for K2, while 16% performed at an average level and 19% at a low level. A notable 23% did not respond to this question. Reflection data revealed that 49% of students correctly recalled their original answer (Remember = 2), but 37% either remembered it incorrectly or did not respond, and only 42% demonstrated visible learning.

Inquiry Knowledge (K3)

The inquiry-based question required students to list variables from the simulation and distinguish between dependent and independent ones. High-level answers (score = 3) clearly and accurately identified multiple relevant variables. For instance, one student explained, "Independent variables include the ear shape and fur color of the parents; the dependent variable is the traits of the offspring." An average-level response (score = 2) might include, "Color and ears," showing understanding of relevant features but lacking classification. Low-level responses (score = 1) were vague or incorrect, such as "The baby rabbits," without elaboration.

Only 23% of students reached a high level for K3, while 47% provided average-level responses and 21% low-level ones (Table 2). As with K2, a significant portion (9%) did not answer. Reflections showed 42% remembered their answer correctly, 37% incorrectly, and 2% provided unrelated or forgotten answers. Learning was visible for 51% of students in this category, suggesting that some students who initially struggled were able to articulate improved understanding in the reflection phase.



Table 2*Student Performance and Learning Outcomes Across Different Variables by Percentage*

Variable	Level	Subject Knowledge (K1)	Subject Knowledge (K2)	Inquiry Knowledge (K3)
Worksheet results in points	High	81.0	41.9	23.3
	Average	12.0	16.3	46.5
	Low	7.0	18.6	20.9
	No answer	0.0	23.3	9.3
Remember: student's answer in reflection phase	Full answer	79.1	48.8	41.9
	Incomplete answer	4.7	9.3	37.2
	Wrong answer	4.7	4.7	2.3
	No answer	11.6	37.2	18.6
Recall: students remembered if their answer was correct or wrong	Correct recall	74.4	46.5	48.8
	Incorrect recall	23.3	37.2	39.5
	No answer	2.3	16.3	11.6
Learning: Visible learning (coded from student responses)	Visible	76.7	41.9	51.2
	Not visible	23.3	58.1	48.8

Reflection Examples Across Indicators

The reflection phase of the study offered valuable insights into students' metacognitive processes and learning trajectories. The Remember indicator assessed whether students could accurately reproduce what they had initially written on the worksheet. For the K1 item, 79% of students produced a full answer, meaning their reflections closely matched their original responses. For instance, one student explained: "Yes, our answer was correct. We both remembered Aa x Aa could lead to 25% white," demonstrating strong retention and accuracy. In contrast, 4.7% gave incomplete answers, such as: "I think we wrote something about recessive traits," reflecting partial recall. Another 4.7% provided wrong answers, such as "We wrote that both parents were white," which did not align with their initial submission. A further 11.6% gave no answer at all.

The Recall indicator captured students' ability to evaluate the correctness of their original responses. For K1, 74.4% of students demonstrated correct recall, reflected in comments like: "We got it right; Aa x Aa produces 25% aa." In contrast, 23.3% showed incorrect recall, misjudging the accuracy of their worksheet responses, as illustrated by statements such as: "We thought we were right, but it seems we weren't." An additional 2.3% gave no answer.

The Learning indicator measured evidence of conceptual development across the activity phases. Students were classified as having visible learning if they maintained a correct answer or improved upon a previous misconception in their reflection. For instance, one student who initially gave a vague response later clarified: "Now I understand that when both rabbits are Aa, they can produce white offspring (aa)," demonstrating conceptual progress. Overall, 76.7% of students were identified as having visible learning, while 23.3% showed no visible learning, indicating no measurable conceptual improvement.

In contrast to K1, results for K2 and K3 reflected greater variation. For K2, 48.8% of students gave a full answer in the Remember task, and 46.5% demonstrated correct recall, while only 41.9% showed visible learning. For K3, 41.9% of students produced full answers, but a substantial proportion (37.2%) gave incomplete responses, and 18.6% did not respond. Nevertheless, 51.2% demonstrated visible learning by revising or deepening their inquiry-based explanations during the reflection phase.

These findings illustrate not only the overall effectiveness of the simulation and reflection cycle in supporting learning but also the individual variability in how students internalized and monitored their understanding. The coded indicators (Remember, Recall, and Learning) offer a nuanced view of students' cognitive and metacognitive development and complement the quantitative distributions presented in Table 2.

Perceived Benefits and Challenges of Collaboration

To address the second research question, student reflections were analyzed to identify perceived benefits and challenges of collaboration. Most students reported that working with a partner supported both their task performance and learning outcomes. One student noted, “Disagreement made us think deeper and consider different perspectives,” highlighting how collaboration encouraged cognitive engagement through dialogue. While overall responses were positive, some students described challenges, such as difficulty reaching consensus or a slower problem-solving process when working in pairs.

Students’ Perceptions of Collaboration Outcomes

A significant majority of the students (78%) perceived that collaboration supported their ability to complete the task successfully. This perception extended to the quality of their work, with 65% indicating that working with a partner led to more accurate responses on the worksheet. Additionally, 82% felt that collaboration helped them overcome challenges they might not have solved independently.

Perceived benefits of collaboration were also evident in broader learning outcomes. Approximately 73% of students reported that working together enhanced their understanding of genetic-related biology concepts. Moreover, 68% indicated that discussing ideas with their partner led to new insights, emphasizing the role of peer interaction in constructing knowledge. Finally, 61% of students believed that collaboration supported their ability to retain information, suggesting perceived long-term learning benefits.

Collaboration Reflections and Links to Performance

Student reflections provided valuable insights into how collaboration shaped their learning experience during the simulation activity. Many students described how peer interaction supported their understanding and helped them make sense of the complex genetics tasks. Several students noted that discussing the task with their partner helped clarify the simulation and underlying inheritance patterns. One student shared, “I understood how to solve the task thanks to collaboration,” while another explained, “Collaboration succeeded because my partner helped me understand,” highlighting the role of joint meaning-making and mutual support.

The complementary nature of teamwork also emerged. Students frequently reported that their partner contributed information or noticed details they had missed. For example, one student reflected, “My partner noticed something I didn’t, which helped us solve the task,” illustrating the benefit of distributed cognition within collaborative inquiry. Additionally, several students emphasized how disagreement contributed to deeper thinking. One remarked, “At first, we argued over definitions, but we ended up finding the right answer,” and another noted, “Disagreement made us think deeper and consider different perspectives,” underscoring the value of constructive conflict in promoting perspective-taking and learning.

Despite these benefits, some students also reported difficulties in collaboration. Approximately 22% of participants noted challenges in reaching consensus, indicating that negotiating shared understanding can be cognitively and socially demanding. Furthermore, 15% felt that collaboration occasionally slowed their task progress. Time constraints and technical limitations, such as simulation delays, also affected the experience for some. One student explained, “We didn’t get to finish because the simulation only started working near the end,” while others mentioned not being able to access key simulation features until the final minutes.

Together, these reflections present a nuanced picture of student collaboration. While most students found that working with a partner enhanced their understanding and task performance, the identified barriers highlight the importance of providing sufficient time, well-designed tools, and scaffolding to support meaningful interaction in inquiry-based, technology-enhanced learning environments.

Importantly, these perceptions were supported by a moderate positive correlation ($r = .42, p < .05$) between students’ reported benefits of collaboration and their subject and inquiry knowledge scores. This suggested that students who valued collaboration also tended to perform better, reinforcing the role of social interaction in supporting cognitive gains.

Self-Evaluation of CPS Skills

Students' self-evaluations of their CPS skills were analyzed across four dimensions: participation, perspective-taking, social regulation, and interdependence (Table 3). Overall, students reported positive perceptions of their collaborative skills, with particularly strong ratings for social regulation ($M = 4.4$, $SD = 0.5$) and perspective-taking ($M = 4.2$, $SD = 1.2$). These results suggest that students generally felt confident in managing group dynamics, resolving disagreements, and considering their partners' viewpoints during the task. Participation ($M = 3.7$, $SD = 1.5$) and interdependence ($M = 3.8$, $SD = 1.4$) were rated slightly lower and showed greater variability, indicating that experiences of individual contribution and mutual reliance were more uneven across the sample.

Table 3*Results of the CPS skills questionnaire*

Dimension	<i>M (SD)</i>
Participation	3.7 (1.5)
Perspective-taking	4.2 (1.2)
Social regulation	4.4 (.5)
Interdependence	3.8 (1.4)

While the full 10-item CPS scale provided a coherent overall measure of collaboration, the internal consistency of individual subscales varied, with lower reliability observed particularly for perspective-taking and social regulation. These psychometric limitations suggest that findings related to specific dimensions should be interpreted with caution. Nevertheless, the self-report data offered valuable insight into how students perceived their roles and interactions in the collaborative learning environment, reinforcing the broader trends observed in the performance and reflection data.

Engagement and Communication in Collaboration

Participation, one of the four CPS dimensions, was strongly evident in students' self-evaluations. A large majority (93%) reported putting significant effort into the task, with 81% identifying as highly active participants. Interestingly, while 65% of students did consider themselves passive, 28% acknowledged moments of low engagement. These patterns suggest that students were not only committed to collaborative success but also aware of their own role and effort within the group.

Perspective-taking, another core CPS dimension, emerged clearly in students' self-reflections. A substantial majority (77%) reported they were willing to change their opinion when presented with new ideas by their partner. Additionally, 86% indicated that they actively clarified their responses to potential misunderstandings. This reflects not only openness to peer perspectives but also a strong orientation toward mutual understanding, which is essential for productive dialogue in collaborative settings.

Group Dynamics and Interdependence

Social regulation, another critical component of key CPS, was clearly reflected in students' awareness of group dynamics and their responses to interpersonal challenges. Nearly all participants (95%) recognized that collaboration skills varied among peers, and 88% reported actively working to resolve disagreements. These findings underscore students' capacity for constructive conflict resolution and their collective commitment to sustaining productive teamwork, which are hallmarks of well-regulated collaboration.

Interdependence, as defined in collaborative learning research by Van den Bossche et al. (2006), was perceived with notable variation among students. While 60% indicated that they relied on their partner's help to complete the task, only 42% felt that their partner would not have succeeded without their contribution. Nevertheless, a strong majority (86%) acknowledged that their partner's success positively impacted their own outcomes. These patterns suggest a nuanced perception of mutual reliance, shaped by individual confidence levels, role asymmetry, and the dynamics of the collaborative experience.

Overall, these results revealed positive self-evaluations of CPS skills, particularly in the areas of social regulation and perspective-taking. Students demonstrated high levels of engagement, a willingness to consider others' viewpoints, and the ability to navigate the social aspects of collaboration. However, the findings on interdependence suggest a complex dynamic, with varied perceptions of mutual dependence among students. This complexity in interdependence perceptions may reflect the challenges of balancing individual contributions with collaborative efforts in group tasks.

Correlations Between Variables

Statistical analysis revealed several significant relationships that offer insights into collaborative learning and problem-solving in biology education (Table 4). Strong positive correlations were found between performance in specific domains (K2 and R2_RC) and inquiry knowledge (K3 and _RC), as well as their recall. This suggests a robust link between the depth of subject knowledge and students' ability to retain and recall information.

In terms of collaborative behavior, initial efforts to collaborate (Partic1) were strongly correlated with ongoing participation (Partic2), indicating that students who initially engage in collaborative efforts are more likely to maintain active participation throughout the process. The correlation between Partic1 and InterDep3 ($r = .72, p < .001$) also suggested that students who perceived themselves as active collaborators were more likely to recognize interdependence in task completion.

Positive correlations between perspective-taking (PeTa1 and PeTa2) and participation (Partic1 and Partic2) highlighted the association between active collaboration and openness to alternative viewpoints. This interplay reinforces the idea that cognitive and interpersonal aspects of CPS mutually support one another.

Table 4

Spearman Correlations Between Performance (K1, K2, K3) and Self-Evaluation of CPS Skills (Partic1, Partic2, Partic3_p, PeTa2, SoReg1, SoReg2, InterDep1)

Variable 1	Variable 2	r_s	p
K2	R2_RC	.60**	.001
K3	R3_RC	.54**	.004
K3	InterDep3	.38*	.044
R2_RC	Partic2	-.42*	.022
Partic1	Partic2	.79***	< .001
Partic1	Partic3_p	.51**	.002
Partic1	PeTa2	.46**	.007
Partic1	SoReg2	.60***	< .001
Partic1	InterDep3	.72***	< .001
Partic2	Partic3_p	.38*	.029
Partic2	PeTa1	.37*	.037
Partic2	SoReg2	.5**	.003
Partic2	InterDep3	.54**	.001
Partic3_p	SoReg2	.42*	.015
Partic3_p	InterDep3	.35*	.050
PeTa2	InterDep3	.43*	.013
SoReg1	InterDep2	-.41*	.018
SoReg2	InterDep3	.88***	< .001
InterDep1	InterDep2	.35*	.046

Social regulation also played a significant role. A strong correlation between conflict resolution (SoReg2) and perceived partner benefit (InterDep3, $r = .88, p < .001$) indicated that students who effectively managed disagreements were more likely to perceive their collaboration as mutually beneficial. Additionally, students who

demonstrated higher social awareness (SoReg1) tended to feel less dependent on their peers (InterDep2), suggesting that an understanding of others' skills contributes to self-efficacy. A negative correlation between SoReg2 and InterDep2 ($r = -.41, p = .018$) further supported the idea that those who are confident in handling conflict feel more capable of working independently within a collaborative structure.

Taken together, these relationships illustrate the interconnected nature of CPS dimensions, including participation, perspective-taking, social regulation, and interdependence, and emphasize that collaboration involves both individual engagement and shared responsibility. While students showed strong theoretical knowledge, their performance in inquiry and their perceptions of interdependence varied. These findings highlight the need to scaffold collaborative interactions in ways that build not only knowledge but also metacognitive and socio-emotional skills essential for effective teamwork.

Discussion

Through the use of an asymmetrical smartphone-based simulation, this research explored how ninth-grade students' subject knowledge, inquiry skills, and CPS skills were fostered and evaluated in a secondary school biology context. The findings offer valuable insights into the cognitive and social dynamics involved in collaborative inquiry-based biology learning, contributing to the growing body of literature on technology-enhanced science education.

Asymmetrical Simulation in Biology Education

An asymmetrical smartphone-based simulation on rabbit genetics was implemented to foster interdependent collaboration by distributing control and information between students. This design mirrors real-world scientific teamwork and aligns with Pea's (1993) notion of digital technologies as cognitive and social scaffolds. In this study, 93% of students reported high effort and 81% reported active engagement, affirming the motivational potential of structured digital inquiry tasks. These findings resonate with Meng and Jumaat (2024), who similarly observed enhanced behavioral engagement, particularly persistence and self-regulation, in a structured online IBL environment.

Beyond engagement, the simulation required students to engage in active knowledge construction and communication, consistent with Vygotsky's (1980) socio-cultural theory and the concept of a zone of proximal development (Rott et al., 2021). Although outcomes varied, several students reported improved understanding through peer interaction, suggesting the value of peer scaffolding within inquiry-based collaboration.

This integration of social constructivist pedagogy with asymmetrical digital tools deepens understanding and supports authentic scientific reasoning, echoing Jeong and Hmelo-Silver's (2016) emphasis on collaboration. The results built on prior work with asymmetrical simulations in photosynthesis-focused inquiry (Rannastu et al., 2019) and in physics using the "Dollhouse Electrical Lab" simulation (Rannastu-Avalos et al., 2023), both of which demonstrated the need for domain-specific scaffolding to optimize learning outcomes.

The findings align with Chen et al. (2023), who used a smartphone-based rabbit genetics simulation within the Go-Lab platform to explore inquiry among culturally diverse learners. Their emphasis on collectivist orientations and computer self-efficacy reinforces the relevance of such tools for inclusive, visual, and inquiry-driven science learning.

Echoing Siiman and Halchevska (2023), the findings of this study also highlight the importance of well-designed scaffolds in interdependent simulations. Their research with Ukrainian students revealed that limited communication (e.g., through chat apps) and complex task demands hindered collaborative outcomes. These results emphasize the need for clearer instructional prompts, particularly those that highlight asymmetry, role dependence, and collaborative strategy, to support meaningful CPS in technology-enhanced environments.

Integrating CPS Skills in a Science Lesson

Integrating subject knowledge, inquiry, and CPS skills in a single lesson presents significant instructional challenges. Performance across subject knowledge (K1, K2) and inquiry skills (K3) illustrates the complexity of this integration, reflecting the multifaceted nature of CPS as described by Graesser et al. (2018) and Salas et al. (2015). This complexity is particularly challenging for students, as they need to understand both abstract concepts and engage in practical, hands-on inquiry.

The results showed that while students outperformed in theoretical understanding, their application of knowledge to inquiry tasks was less consistent, aligning with Pedaste et al. (2015), who highlighted difficulties in

transitioning from knowledge acquisition to application in inquiry-based science education. Similar challenges were noted in other studies (Lazonder & Harmsen, 2016; Mäeots & Pedaste, 2014), especially when digital technologies are involved. Performance on the subject knowledge questions also revealed key differences, see Table 2. The K1 task required students to explain how a black rabbit pair could produce white offspring, prompting them to explore the simulation and justify the genetic mechanisms. Students' strong results on this task suggest that prior theoretical knowledge supported their reasoning and interpretation. In contrast, the K2 task involved identifying the precise parental traits needed to achieve a 50% distribution of offspring ear types. This required more abstract reasoning and deeper analysis of variable relationships in the simulation, which likely challenged students who lacked prior exposure to this specific concept. The differing performance between K1 and K2 underscores how varying task demands interact with prior knowledge and inquiry skills in shaping students' success in CPS-oriented science learning.

These findings underscore the need for structured, scaffolded inquiry processes to help students connect theory to practice. As Mäeots and Pedaste (2014) suggested, inquiry-based approaches must be intentionally supported by pedagogical tools that guide students from conceptual understanding to procedural fluency. This research highlighted how the integration of CPS frameworks, like those by Griffin and Care (2014) and Hesse et al. (2014), can shed light on the link between knowledge application and collaborative efforts. Magana et al. (2024) further emphasized that structured collaborative frameworks and scaffolding can promote positive interdependence, an area requiring further focus in this study. Li et al. (2025) pointed to an association between foundational cognitive skills and CPS task performance, which further suggests that better scaffolding of the K2 and K3 tasks would have improved the results by reducing cognitive load.

Balancing teamwork (e.g., participation, regulation, perspective-taking) with taskwork (e.g., knowledge recall, experimental design) highlights a core issue in CPS integration. This tension is aligned with the "21st-century skills" framework, which advocates for blending cognitive and socio-emotional capacities (OECD, 2017). In the simulation-based biology lesson, fostering both collaborative and scientific inquiry skills was essential, indicating that CPS should be central to meaningful science learning.

Correlation Between Perceived Collaboration Benefits and Performance

While much of the evidence for collaboration effectiveness came from qualitative reflections, these perceptions were also supported by statistical analysis. A moderate positive correlation ($r = .42, p < .05$) was found between students' perceived collaboration benefits and their assessment performance, suggesting that students who felt their learning was enhanced by collaboration also performed better in both subject knowledge and inquiry-based assessments.

This finding aligns with Järvelä et al.'s (2016) concept of socially shared regulation in computer-supported collaborative learning (CSCL), where peers co-construct knowledge and regulate motivation and engagement collectively. These dynamics explain why students who experience successful collaboration tend to show improved academic outcomes. Additionally, it emphasizes the value of examining metacognitive aspects of collaboration alongside performance metrics, an approach supported by Wise and Schwarz (2017).

However, not all students found collaboration straightforward. About 22% reported difficulty reaching consensus, and 15% felt that working with a partner slowed their task progress. These findings underscore that collaboration, while beneficial for many, is not universally effective, particularly in time-limited or technology-mediated environments. Future research and instructional design should address how to support students who struggle with collaboration due to conflict, pacing mismatches, or unequal contributions. Understanding these barriers is crucial for refining collaborative frameworks and ensuring equitable participation among diverse learner profiles.

Social Regulation and Interdependence in Adolescent Collaborative Learning

Students' self-evaluations revealed generally positive perceptions across the four CPS dimensions, particularly in participation and social regulation. The social regulation dimension emerged as a relative strength in both self-reported and observed behaviors: 95% of students acknowledged differences in collaborative skills among peers, and 88% actively worked to resolve disagreements. These findings align with the CPS frameworks proposed by Hesse et al. (2014) and OECD (2017), highlighting students' ability to maintain shared understanding and manage group processes. Similarly, 86% of students reported clarifying their thinking in response to misunderstandings, and 77% indicated that their partner's ideas prompted them to revise their own responses. These peer exchanges



resonate with Vygotsky's socio-cultural theory and reflect the cognitive benefits of collaboration within the zone of proximal development (Rott et al., 2021).

In contrast, perceptions of interdependence were more varied. While 60% of students felt they relied on their partner's help, only 42% believed their partner depended on them, suggesting an asymmetry in perceived mutual reliance. Nevertheless, 86% acknowledged that their partner's success contributed to their own, supporting Johnson and Johnson's (1999) argument that positive interdependence must be intentionally scaffolded. This mirrors findings by Siiman and Halchevska (2023), who observed heightened awareness of interdependence without consistent gains in performance in hidden-profile tasks.

Although the internal consistency of the full 10-item CPS scale was acceptable, individual subscales, particularly perspective-taking, social regulation, and interdependence, demonstrated lower reliability. Therefore, while disaggregated findings should be interpreted cautiously, triangulation with reflection data and classroom observations increases confidence in the conclusion that students meaningfully engaged in collaborative processes. The asymmetrical task structure appears to have supported both social and cognitive scaffolding, but findings also point to the need for further instructional support to foster balanced and reciprocal interdependence in adolescent science education.

Technology-Enhanced Collaborative Learning in Biology

The findings demonstrated that the smartphone-based simulation supported both cognitive engagement and collaborative interaction. A large majority of students (93%) reported that they made a strong effort during the activity, and 81% described themselves as highly active participants. These responses highlight the motivational potential of well-structured digital tools in inquiry-driven science tasks, consistent with previous findings by De Jong et al. (2023) and Chen and Tsai (2021). Similarly, Meng and Jumaat (2024) observed that structured inquiry-based environments fostered persistence and self-regulated learning, outcomes that were mirrored in the students' sustained focus and adaptive problem-solving strategies. Notably, the asymmetrical simulation required continuous coordination and verbal negotiation between partners, aligning with Pea's (1993) conceptualization of technology as both a cognitive and social scaffold. Rather than simply functioning as a content delivery tool, the simulation acted as a catalyst for collaborative reasoning, demonstrating how digital design features can meaningfully shape student interaction in biology education.

A systematic review by Agustin et al. (2024) affirmed the effectiveness of virtual labs, particularly when paired with instructional scaffolds. This paralleled the use of structured tasks and teacher guidance to support inquiry in abstract biological domains employed in this study. Similarly, Sui et al. (2023) showed how animated simulations like "Methane Mystery" can develop scientific reasoning through dynamic, visually rich inquiry environments.

These findings align with Ouyang et al. (2022), who emphasized digital tools' role in promoting interdisciplinary thinking and student agency. However, limitations emerged: students sometimes experienced frustration due to delays or unclear task expectations. These challenges are consistent with concerns raised by Bell et al. (2009) and Kirschner et al. (2006) about cognitive overload and technical disruptions. Supporting Looi et al.'s (2015) framework, the results stress that the impact of smartphone-based learning depends on intentional pedagogical support. While the simulations encouraged peer dialogue and engagement, improvements in task clarity and interface responsiveness are necessary for full effectiveness. Ultimately, technology's potential to support CPS hinges on its alignment with inquiry goals, student cognition, and structured teacher support. This underscores the central role of pedagogical design in delivering equitable and scalable science education.

Reflection and Metacognition in Collaborative Science Learning

An important dimension of the study was the inclusion of structured reflection and self-evaluation activities, emphasizing the role of metacognition in collaborative science learning. Students' ability to accurately recall their answers (e.g., 79.1% for K1) and reflect meaningfully on their performance aligned with Flavell's (1979) concept of metacognitive regulation, illustrating how reflection can enhance awareness of cognitive processes.

This mirrors Bransford et al. (2000), who highlighted the importance of reflection in connecting new experiences with prior knowledge, and extended Schön's (2017) reflection-in-action and reflection-on-action into collaborative, inquiry-based contexts. Similarly, Kolb's (1984) experiential learning cycle, where reflection drives conceptualization and future action, was observed in students' post-task evaluations. Importantly, this process



contributed to students' scientific reasoning, as predicted by Furberg (2009), and supported the development of reflective judgment, which matures with age and experience (King & Kitchener, 2004).

The integration of constructivist learning principles (Piaget, 1976; Dewey, 1986) with technology-enhanced collaborative learning shows promise. Asymmetrical simulations engage students in co-constructing knowledge (Driver et al., 1994), but greater emphasis is needed on scaffolding practical skills and scientific reasoning strategies, such as control of variables (Schwichow et al., 2016). Scaffolding in technology-enhanced environments, as Kaldaras et al. (2024) suggest, addresses gaps in inquiry and problem-solving skills, especially when transitioning from reflection to performance.

Despite the potential of reflection activities, results indicated varied success in translating reflection into improved inquiry outcomes, suggesting that metacognitive gains do not automatically translate into better performance without structured support. This emphasizes the need for targeted scaffolding of reflective practices, particularly for adolescent learners whose metacognitive abilities are still developing (Lichtenberger-Majzikné & Fischer, 2017). Despite high engagement, some students left reflective questions unanswered or misjudged their responses, highlighting the complexity of integrating reflection into collaborative science tasks.

The connection between students' perceptions of collaboration and their performance underscores the importance of fostering positive attitudes toward collaborative learning. The high levels of social regulation reported align with the CPS framework proposed by Hesse et al. (2014), suggesting promising directions for future research in this age group. Consistent with Perkins and Salomon (1989), effective reflection may facilitate the transfer of CPS skills across different tasks and learning environments.

Conclusions and Implications

This study addressed a core challenge in contemporary science education: the meaningful integration of CPS skills with subject knowledge and IBL. Although CPS is increasingly recognized as a critical 21st-century competency, its systematic implementation within everyday secondary school science lessons remains limited. Responding to calls from researchers such as Care and Kim (2017), this study explored how instructional strategies, particularly those leveraging digital tools, can embed CPS into everyday teaching practices.

By employing a smartphone-based, asymmetrical simulation, the study provided a concrete example of how digital technologies could concurrently support the development of CPS, inquiry skills, and content-specific understanding. The simulation's asymmetrical design required students to assume distinct but complementary roles, encouraging joint reasoning, interdependence, and mutual problem-solving. These features illustrate the practical application of structured collaborative learning principles and highlight how well-designed tasks can foster both cognitive and social dimensions of student learning.

Situated in the Estonian educational context, the findings offer broader international relevance. The challenges explored, including the integration of CPS with IBL through digital scaffolds, are shared across many educational systems striving to develop deeper cognitive and social competencies. As global curricula increasingly emphasize the importance of active, collaborative, and technologically supported learning, this study demonstrated that thoughtfully designed simulations can serve both instructional and developmental functions.

Importantly, while the internal consistency of some CPS self-assessment subscales was limited, the use of multiple data sources, including worksheets, reflection responses, and classroom observations, enhanced the robustness of the findings. This triangulated approach offered a nuanced perspective on how students engaged with collaborative tasks, allowing for a more comprehensive understanding of CPS development within inquiry-based contexts.

The study's design, which integrates inquiry, collaboration, and subject matter into a single lesson, reinforced the pedagogical value of simulations not only as tools for knowledge application but also as frameworks for social interaction and metacognitive reflection. However, the results also underscore the importance of carefully structured tasks and targeted pedagogically aligned scaffolds to support reciprocal interdependence and sustained cognitive engagement.

This study offered evidence-based insights into how smartphone-supported simulations can facilitate the simultaneous development of content knowledge, inquiry skills, and collaborative skills within authentic science lessons. Rather than reiterating generic claims, the findings pointed to specific mechanisms, such as asymmetrical role distribution and reflection-based scaffolding, that promote deeper engagement with both disciplinary concepts and collaborative processes. These insights can inform future instructional design and educational research focused on embedding CPS meaningfully into everyday science education.

Limitations

This study acknowledges several methodological limitations that should be considered when interpreting the findings. First, the study employed a single-lesson design without a control group, which restricts the generalizability of the results and limits the ability to draw causal inferences about the effectiveness of the intervention. While the findings offer valuable insights into how CPS skills can be supported through asymmetrical simulations and IBL, they reflect a specific instructional context and time frame.

Second, the study relied on students' self-evaluations to assess collaborative problem-solving skills. Although this method provides access to students' perceptions of their engagement and behavior, it is subject to potential bias. Self-reported data may not always align with actual performance, particularly in cases involving complex social processes, such as collaboration. Future research should consider triangulating self-assessments with additional sources of evidence, such as peer assessments, teacher ratings, or observational coding frameworks.

A further methodological concern involves the internal consistency of the CPS Skills Questionnaire. While the participation subscale demonstrated acceptable reliability, the perspective-taking, social regulation, and interdependence subscales showed low or negative Cronbach's alpha values. These results likely reflect the small number of items per subscale, variation in students' interpretations of the items, or the inherent difficulty of self-assessing nuanced social behaviors. The reverse-coded item within the Participation dimension was handled correctly and did not impair internal consistency, suggesting that the directionality of items was processed appropriately by students. Nevertheless, these limitations underscore the need to refine the CPS measurement instrument, for example, by expanding the number of items per subscale and including externally validated measures of collaboration.

Overall, these constraints highlight the importance of future research employing longitudinal designs, the inclusion of control groups, and the use of multiple assessment methods to further validate and extend insights into collaborative learning processes in inquiry-based science education.

Declaration of Interest

The authors declare no competing interest.

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Appendix 1. Student worksheet version A

A NAME _____ AGE _____ GROUP NUMBER _____

In today's lesson, you will explore the principles of heredity and complete a task on a smartphone with your partner. You have 20 minutes to complete the worksheet.

1. THEORY: PRINCIPLES OF HEREDITY

Traits characteristic of an organism are generally determined by multiple genes, but sometimes a single gene determines a specific trait. If one gene determines a trait, organisms inherit two alleles for that trait, one from each parent. These two alleles form the genotype.

Let us assume that the fur color of a rabbit species is determined by one gene, and the color can be either black (A) or white (a):

- A – allele that causes black fur color
- a – allele that causes white fur color

This means there are three possible genotypes for a rabbit's fur color: AA, Aa, and aa. The genotype combination Aa is the same as aA. The Aa (aA) genotype shows that the offspring has inherited one allele from each parent. In such cases, typically only one trait is expressed, the one determined by the dominant allele, while the trait linked to the recessive allele remains unexpressed.

By convention, dominant alleles are written with an uppercase letter (e.g., A or B), and recessive alleles with a lowercase letter (e.g., a or b).



2. CONDUCTING EXPERIMENTS

In conducting experiments, it is important to distinguish between independent and dependent variables. What is the difference between them?

An independent variable is something you can change in your experiment. To determine the outcome of the experiment, you measure the dependent variable, which is affected by the independent variable. That's why it's called dependent!

Note: The same variable might be independent in one experiment and dependent in another.

3. TASK

Take your smartphone and open the link: lingid.ee/alleel. In the field "Enter your group number," type the group number written at the top of this worksheet. Click the Join button to launch the simulation.

NB! Do not look at your partner's smartphone screen. You may only talk about what you read or see on your own screen.

1. In this computer simulation, black rabbits can give birth to a white offspring. How is this possible? Justify your answer.
2. List all the independent variables in this simulation.
3. Explain what traits the two white rabbits in this simulation must have so that they produce an offspring with a 50% chance of having floppy ears or upright ears.

Appendix 2. Student worksheet version B

B NAME _____ AGE _____ GROUP NUMBER _____

In today's lesson, you will explore the principles of heredity and complete a task on a smartphone with your partner. You have 20 minutes to complete the worksheet.

1. THEORY: PRINCIPLES OF HEREDITY

Traits characteristic of an organism are generally determined by multiple genes, but sometimes a single gene determines a specific trait. If one gene determines a trait, organisms inherit two alleles for that trait, one from each parent. These two alleles form the genotype.

Let us assume that the fur color of a rabbit species is determined by one gene, and the color can be either black (A) or white (a):

- A – allele that causes black fur color
- a – allele that causes white fur color

This means there are three possible genotypes for a rabbit's fur color: AA, Aa, and aa. The genotype combination Aa is the same as aA. The Aa (aA) genotype shows that the offspring has inherited one allele from each parent. In such cases, typically only one trait is expressed, the one determined by the dominant allele, while the trait linked to the recessive allele remains unexpressed.

By convention, dominant alleles are written with an uppercase letter (e.g., A or B), and recessive alleles with a lowercase letter (e.g., a or b).

2. CONDUCTING EXPERIMENTS

In experiments, it is important to distinguish between independent and dependent variables.

What's the difference between them?

An independent variable is something you can change in your experiment. To evaluate the outcome, you measure a dependent variable, which changes in response to the independent variable. That's why it's called *dependent*!

Note that the same variable can be dependent in one study and independent in another.

3. TASK

Take your smartphone and open the link: lingid.ee/tunnus. In the field "Enter your group number," type the group number written at the top of this worksheet. Click the Join button to launch the simulation.

NB! Do not look at your partner's smartphone screen. You may only talk about what you read or see on your own screen.

1. In this computer simulation, black rabbits can give birth to a white offspring. How is this possible? Justify your answer.
2. List all the dependent variables in this simulation.
3. Explain what traits the two white rabbits in this simulation must have so that they produce an offspring with a 50% chance of having floppy ears or upright ears.

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