



Abstract. *Inquiry-based learning structured through the 5E learning cycle is widely recognised for fostering conceptual understanding and scientific reasoning. However, optimal strategies for supporting inquiry in primary classrooms remain debated. Empirical comparisons of hands-on, simulation-based, and blended inquiry approaches in primary science classes remain limited, particularly with respect to their effects on scientific inquiry skills and affective outcomes. This study developed a simulation-based inquiry module aligned with the 5E learning cycle and compared three inquiry approaches using a quasi-experimental pre-test and post-test design across six intact sixth-grade classes. Scientific inquiry skills and affective outcomes were measured before and after the inquiry activities. ANCOVA revealed significant group differences in several integrated scientific inquiry skills, including transforming data, interpreting data, formulating hypotheses, and controlling variables. Both simulation-based and blended inquiry approaches improved higher-order scientific inquiry skills and learning motivation, with the blended approach showing the most consistent effects. The effects were more pronounced in integrated inquiry skills and task commitment than in basic inquiry skills and some affective subcomponents. These findings indicate that simulations are most effective when integrated sequentially with hands-on experimentation in primary science learning.*

Keywords: *simulation-based inquiry, blended inquiry, science inquiry skills, affective domain, primary science education*

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COMPARING SIMULATION-BASED AND BLENDED INQUIRY LEARNING IN PRIMARY SCIENCE: EFFECTS ON SCIENCE INQUIRY SKILLS AND AFFECTIVE OUTCOMES

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Introduction

Developing students' ability to investigate scientific problems and construct evidence-based explanations is considered an important goal of contemporary science education. In this context, inquiry-based learning has been widely recognised as a central approach to improve students' understanding of scientific concepts and promote scientific problem-solving skills and attitudes (Kirschner et al., 2006; Kruit et al., 2018; van Uum et al., 2017). Also, various inquiry-based approaches have been proposed to strengthen students' scientific inquiry competencies (Cevik & Surmeli, 2024; Kim & Kim, 2024). However, implementing inquiry-based science teaching in primary school settings remains a challenge for both students and teachers. Students frequently struggle to make meaningful connections across inquiry phases and often remain at the level of simple confirmation activities (Lee et al., 2004; McDonald & Songer, 2008; van Zee et al., 2005). These challenges are particularly evident in primary science classrooms (Heppt et al., 2023), where inquiry-based learning often imposes substantial cognitive demands on students, including controlling variables, interpreting data, and drawing evidence-based conclusions (Zohar, 2006).

Most primary school teachers, many of whom are generalists rather than science specialists, experience additional difficulties in designing and implementing inquiry-based science teaching in their classrooms (Kim & Kim, 2024; Lee et al., 2004; Lewis, 2019; van Zee et al., 2005). They are often less confident in facilitating science inquiry classes or experience difficulties implementing open inquiry because they must prepare lessons across multiple subjects (Radloff & Capobianco, 2021). In primary schools, it can be difficult for students to carry out scientific inquiry activities on their own from beginning to end, and since individual student differences exist in a wide variety, the success of learning through inquiry activities cannot always be ensured (Lazonder & Harmsen, 2016; van Schijndel et al., 2018; Zion et al., 2004). In practice, primary teachers manage large, mixed classes, struggle to address individual misconceptions, and, pressed for time, sometimes substitute textbooks or worksheets for hands-on work (de Jong et al., 2023). Apart from a minority with science expertise, many rely on inquiry manuals and activity guides. Some teachers



even equate scientific inquiry learning to behaviour or device handling experienced during experiments, and tend to overlook key processes such as reasoning, modelling, and argumentation (Gillies, 2020). These difficulties suggest the need for structured guidance and scaffolding to reduce cognitive load for students and teachers and to support inquiry learning through step-by-step assistance (Hmelo-Silver et al., 2007). Therefore, structured learning resources and guidance strategies are needed to help teachers manage inquiry activities more effectively and to help students carry out inquiry tasks such as variable manipulation, observation, and data interpretation step by step (Heppt et al., 2023; Lazonder & Harmsen, 2016). Among the major tools recently distributed in classroom practice to support science inquiry activities, web-based simulation content supports students' inquiry learning and helps teachers structure and guide the inquiry process (Srisawasdi & Panjaburee, 2015).

Well-designed simulation environments provide students opportunities for conceptual understanding and scientific reasoning (Falloon, 2019) and can enhance the feasibility and effectiveness of inquiry classes (Chernikova et al., 2020; Banda & Nzabimana, 2021; Rahmawati et al., 2022). However, concerns have been raised that heavy reliance on digital devices may diminish the role of hands-on inquiry. Given the challenges associated with effective hands-on work, it remains unclear whether simulations are more beneficial when used independently or in conjunction with physical experiments. Addressing this issue requires a detailed examination of the challenges inherent in inquiry-based learning, the role of scaffolding, and the specific contribution and limitations of simulations.

Challenges of Inquiry-Based Learning in Primary Science

From the teacher's perspective, primary school teachers often lack scientific content knowledge as generalists rather than specialists in specific subjects, which makes it difficult for them to design and implement inquiry-based classes and often leads them to rely on textbooks and activity guides (Appleton, 2003). These problems can limit the systematic development of science teaching competencies among primary school teachers (Dah et al., 2024; Schwartz & Gess-Newsome, 2008). In this regard, scientific inquiry is often reduced to hands-on experimental activity, focusing only on the experience itself, and higher-order thinking such as hypothesis generation, variable control, data interpretation, and drawing conclusions is often insufficiently addressed (Gillies, 2020). This structural constraint shapes teachers' actual teaching patterns, and it can be seen that most primary school teachers' inquiry-class approaches remain at the confirmation level of inquiry, leading to a tendency not to move toward open inquiry (Ireland et al., 2014).

These constraints can affect the quality of the scientific inquiry experiences available to students in primary science classrooms. Inquiry learning places high cognitive demands on conceptual understanding, procedural performance, and metacognitive control simultaneously, so inadequate individual support can lead to frustration and reduced participation in the learning process (Chen et al., 2026). In particular, primary school students have difficulty planning and carrying out the entire inquiry process autonomously, and the variation among individual learners is also large (Lazonder & Harmsen, 2016; van Schijndel et al., 2018; Zion et al., 2004). In addition, reasoning for verification, such as variable control, is an area that is difficult for students to develop voluntarily (Kuhn & Dean, 2005), and if sufficient scaffolding is not provided, students tend to remain at the level of superficial performance without linking inquiry activities with broader scientific concepts (Morris, 2025). Therefore, effective inquiry-based science teaching requires structured support that facilitates students' cognitive processes, reduces their cognitive load, and eases teacher workload.

Scaffolding and Support Tools in Inquiry-Based Learning

The effectiveness of inquiry learning varies depending on the quality and method of guidance provided to students. Because science inquiry learning requires a combination of conceptual understanding, procedural performance, and reasoning, scaffolding that manages cognitive burden, guides the thinking process step by step, and structures inquiry performance is essential. In learning activities that require higher-order cognitive functions, such as problem-based learning and inquiry learning, proper scaffolding helps regulate cognitive load and promote learning by supporting learners as they gradually solve difficult challenges (Hmelo-Silver et al., 2007). A meta-analysis of guidance in inquiry learning found that various forms of support significantly improved learners' inquiry performance, with the strongest effects when procedural and conceptual guidance were provided together (Lazonder & Harmsen, 2016). This suggests that an appropriate level of structure and guidance in science inquiry can positively affect learning quality.

Insufficient scaffolding can lead students to perform at a superficial level, failing to connect inquiry activities to broader scientific concepts (Morris, 2025). Providing structured learning resources for inquiry-based science teaching can therefore significantly influence students' learning outcomes. Scaffolding in science inquiry learning can take vari-



ous forms depending on the learning environment and teaching context, ranging from verbal explanations, questioning, reading materials, and visual aids from teachers to digitally supported web-based learning content. In primary science teaching, real-time scaffolding by teachers is important because it can respond sensitively to learners' needs. However, most teachers have difficulty responding spontaneously to students' science learning situations and tend to adhere to pre-planned class structures (Sasse et al., 2025). In addition, difficulties in classroom management, student response, and switching between inquiry stages were also observed in a study that analysed the implementation of inquiry classes of pre-service primary school teachers (Yoon et al., 2012). Therefore, teachers' individual capabilities alone may be insufficient to provide consistent and effective scaffolding. Recently, as an alternative to compensating for the limitations of teacher-dependent scaffolding, embedded scaffolding inherent in teaching tools has attracted increasing attention. Unlike the flexible support that teachers provide in real time during learning activities, embedded scaffolding refers to support that is designed in advance and incorporated into learning materials or tools in a structured form (Saye & Brush, 2002). In this context, technology-enhanced inquiry tools can provide structured scaffolding that supports science learning and helps teachers guide inquiry processes more effectively (Kim et al., 2007). From printed learning materials such as workbooks and learning guides to interactive digital inquiry modules, well-designed scaffolding resources can provide consistent support for students while reducing teachers' need to provide continuous real-time guidance (Al Mamun et al., 2020; Belland, 2017). Recent studies suggest that digital inquiry tools, such as computer simulations, can provide structured guidance and immediate feedback, helping students manipulate variables, interpret results, and develop conceptual understanding during inquiry activities (Kaldaras et al., 2024).

Simulation-based Science Inquiry Learning

Immersive technologies such as virtual experiments are increasingly applied in science classrooms, as they allow learners to make abstract concepts more concrete, provide repeated experiences, and support understanding of complex phenomena (Chernikova et al., 2020; Hillmayr et al., 2020). As teaching tools, simulations support inquiry through repeated practice, visualisation, variable manipulation, and instant feedback, and help teachers manage the inquiry process more systematically (Srisawasdi & Panjaburee, 2015). In science education, simulations allow students to investigate scientific phenomena in virtual environments where experiments can be repeated safely and without the material constraints often present in school laboratories (Hillmayr et al., 2020). Simulations are particularly useful for representing phenomena that are difficult to observe directly, such as microscopic processes or large-scale ecological systems, and can help students connect abstract scientific concepts with visual representations (Pellas et al., 2020; Sirakaya & Alsancak Sirakaya, 2022). In addition, virtual experimentation enables repeated manipulation of variables and immediate observation of results, which can support conceptual understanding and sustained engagement during inquiry activities (Banda & Nzabahimana, 2021; Chernikova et al., 2020; Rahmawati et al., 2022; Zhang & Wang, 2021). Moreover, visual-interactive features and immediate feedback can positively influence student interest, motivation, and attitudes towards science (Güler & Cengiz, 2025; Schwarz & White, 2005). Simulation-based environments impose substantial cognitive demands on learners, requiring coordination of variable manipulation and conceptual reasoning. Without an appropriate learning structure, students may struggle to connect virtual exploration with deeper scientific understanding. Because the effectiveness of inquiry-based learning depends on the presence and type of teaching guidance, the use of simulations does not guarantee educational effectiveness. Virtual experiments can complement scientific inquiry learning by supporting inquiry processes and conceptual understanding when accompanied by appropriate guidance and a well-structured inquiry design (Wörner et al., 2022). This suggests that the effectiveness of simulation-based inquiry depends not only on the simulation itself but also on how it is integrated into the overall inquiry process. Therefore, to make effective use of the inquiry-supporting features of simulations in classroom practice, learning activities should be carefully designed around the entire inquiry process.

The 5E learning cycle (Engage–Explore–Explain–Elaborate–Evaluate) has been widely adopted as a structured learning model that promotes conceptual change by organising learning through interconnected inquiry phases (Bybee et al., 2006; Polanin et al., 2024). Within the 5E learning framework, simulation-based activities have been shown to support inquiry processes such as variable manipulation and pattern identification (Koyunlu Ünlü & Dökme, 2022). During the Explore phase, students can actively engage in inquiry by manipulating variables and examining resulting patterns, whereas the Explain and Elaborate phases support deeper understanding by enabling learners to construct explanations and apply concepts to new situations. Thus, simulations can be integrated across different phases of inquiry, and the 5E model provides a coherent framework for organising simulation-based inquiry in science learning. Nevertheless, previous research on simulations has primarily been conducted in secondary and higher education contexts, focusing on cognitive outcomes such as conceptual understanding and academic achievement,

while studies that simultaneously examine inquiry skills and affective characteristics in primary science contexts remain relatively limited (Almasri, 2022). Furthermore, many studies comparing simulations with hands-on experiments have treated the two approaches as alternatives, whereas empirical research investigating the effects of blended inquiry that integrates the two in a complementary manner is still scarce (Rutten et al., 2012; Wörner et al., 2022). Therefore, in the context of primary science inquiry, it is necessary to examine whether simulations function as substitutes for authentic inquiry or as complementary resources that can enhance learning when combined with hands-on inquiry.

Research Aim

In primary science, it remains uncertain whether replacing hands-on inquiry with simulations or combining both approaches yields superior cognitive and affective learning outcomes. To address this question, the present study developed a simulation-based inquiry module aligned with the 5E learning cycle and compared three conditions: hands-on inquiry, simulation-based inquiry, and blended inquiry implemented sequentially. This study focused on students' scientific inquiry skills and their affective outcomes during inquiry. Inquiry skills represent a core cognitive component of scientific learning, including formulating hypotheses, controlling variables, and interpreting data, and are especially challenging for primary students. Affective outcomes, measured through learning motivation and task commitment, reflect the sustained effort required during inquiry and are particularly important in primary education, when students' long-term orientation toward science is established. Therefore, the study addressed the following two research questions.

First, are there significant differences in the scientific inquiry skills of primary students in hands-on, simulation-based, and blended inquiry conditions?

Second, how do the three inquiry conditions differ in their effects on students' learning motivation and task commitment?

Research Methodology

General Background

This study was conducted at a primary school that emphasises scientific inquiry skills as central learning outcomes according to the national science curriculum. Sixth grade is the final year of primary science education in Korea. The students develop various scientific inquiry skills before advancing from primary school to lower-secondary school, according to the curriculum. Despite curricular emphasis, the actual implementation of inquiry-based science learning in Korean primary classrooms continues to face various challenges, including limited resources, time constraints, and difficulties providing individualised inquiry guidance. In this context, to identify effective teaching approaches for primary science inquiry classes, this study used a quasi-experimental pre-test and post-test design to investigate the effects of three inquiry conditions, namely hands-on inquiry, simulation-based inquiry, and blended inquiry, on sixth-grade students' scientific inquiry skills, learning motivation, and task commitment. The implementation was carried out as part of the regular primary science curriculum in the second semester of 2025, and cognitive and affective outcomes were compared across the three conditions.

Participants

This study involved six sixth-grade classes from a primary school in an urban area of the Republic of Korea to minimise contextual variation related to the implementation of the school's digital infrastructure and curriculum. Sixth-grade students were selected because the Korean primary science curriculum at this level emphasises basic and integrated inquiry skills, which align with the purpose of the study. Because science learning in the curriculum is normally conducted at the classroom level, intact classes were used rather than randomly assigned individual students to conditions. Therefore, the sample size was determined by existing class enrolment rather than by an a priori sample size calculation. All six sixth-grade classes at the participating school were included as subjects in this study, and two intact classes were assigned to each of the three inquiry learning conditions in the quasi-experimental design. A total of 121 sixth-grade students initially participated in the study. All participants were regular students and were informed of the study's purpose and procedures before the inquiry activities and pre-test administration. Participation was voluntary, and parental informed consent was obtained prior to the study. The study was approved by the Institutional Review Board of Kangwon National University (No. KWNUIRB-2025-11-011-001). However, only



data from students who completed the pre-test and post-test questionnaires were included in the final analysis. The final analytic sample consisted of 31 students in the hands-on inquiry group, 34 students in the simulation inquiry group, and 36 students in the blended inquiry group (Table 1).

Table 1
Demographic Characteristics of Participating Students by Inquiry Group

Gender	Hands-on (n=31)	Simulation (n=34)	Blended (n=36)	Total (n=101)
Male	18	20	22	60
Female	13	14	14	41

Development of the Simulation-based Inquiry Module

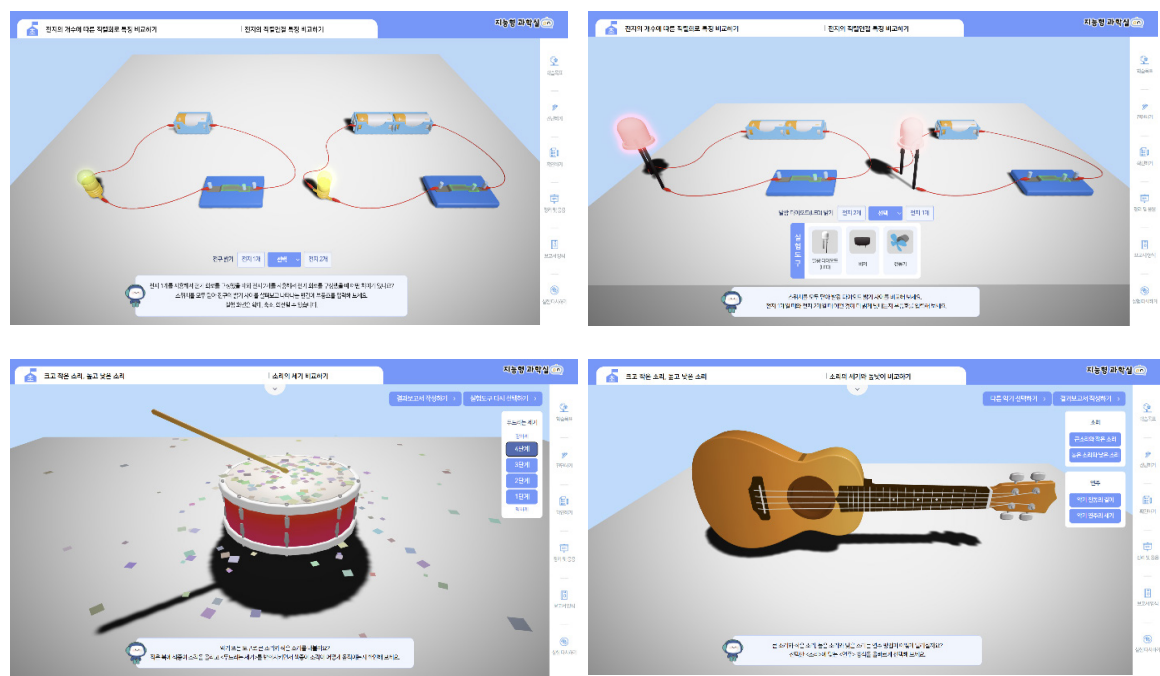
To develop a simulation-based inquiry module, the 2022 Korean national science curriculum and related literature were analysed to identify inquiry topics in which students frequently experience difficulties during hands-on experimentation. Based on this analysis, a preliminary set of candidate topics was identified. To further inform the selection, an online survey with practicing primary school teachers was conducted to gather their perspectives on which experimental topics pose the greatest teaching challenges in actual classroom settings. Taking both the curriculum-based analysis and teacher input into account, two physics-domain topics were selected. Next, two inquiry themes within the physics domain that frequently pose challenges for experimental implementation in primary classrooms were selected for simulation-based inquiry: comparing electric circuits using series-connected batteries and investigating the pitch and loudness of sound. These topics often require substantial materials or yield inconsistent experimental results and higher-order cognitive demands, making them suitable candidates for simulation-based environments.

The simulation content was developed as a web-based application using Babylon.js, a WebGL-based 3D rendering engine that enables interactive visualisation and variable manipulation within a standard web browser. The researchers designed all aspects of the module, including inquiry activity scenarios, learning content, on-screen text, activity structure, expected results, and feedback messages, and provided these specifications to a professional development team that was solely responsible for the technical implementation. This collaborative process was carried out iteratively from the prototype stage through to the final version to ensure the pedagogical alignment with the 5E learning cycle and the accuracy of the scientific content. The completed module was reviewed by four experts in science education, comprising university faculty members and experienced primary science teachers, to evaluate alignment with the national curriculum, clarity of terminology, and appropriateness for primary students. Based on expert feedback, revisions to the structure, sequence of activities, and language were made prior to implementation.

The simulation for science inquiry activity in primary school was structured according to the 5E learning cycle (Engage–Explore–Explain–Elaborate–Evaluate). Each phase was aligned with a corresponding inquiry process so that students could experience a coherent sequence of question posing, exploration, explanation, and application. In the Engage phase, a motivating question is presented to provoke students’ prior conceptions and spark curiosity. The Explore phase provides opportunities to manipulate relevant variables in a virtual environment and observe the resulting changes. During the Explain phase, students organise and articulate their understanding based on the results of the virtual experiments. The Elaborate phase extends the learnt concepts to new situations, and the Evaluation phase requires students to demonstrate their understanding through embedded assessment tasks. The simulation was designed to be implemented during regular science lessons without the need for additional laboratory materials, thereby minimising classroom constraints and increasing accessibility for teachers and students. The simulation developed allows students to actively manipulate variables by selecting experimental tools and designing experiments autonomously. In the electricity module, students construct virtual circuits by choosing batteries, wires, and switches, and observe how changes in battery configuration affect circuit behaviour. In the sound module, they explore pitch and loudness by adjusting the length of virtual instruments and the strength of vibrations. This interactive structure enables students to repeat experiments freely and to compare multiple conditions, fostering self-directed inquiry and promoting deeper conceptual understanding. These features enable simulation to function as a flexible and repeatable complement to hands-on experiments in primary science education, particularly when physical experimentation is difficult to conduct or reproduce (Figure 1).



Figure 1
Screenshots of the Web-based Simulation



Note. The top images are the user interface for “Comparing characteristics of series circuits by the number of batteries”, and the bottom images are the user interface for “Loud and soft sounds, High and low sounds”.

Implementation of the Three Inquiry Conditions

To compare the effects across the three inquiry conditions, six intact sixth-grade classes were assigned to one of three groups, with two classes per condition: a hands-on inquiry group conducting physical experiments only, a simulation inquiry group using only the web-based simulation module, and a blended inquiry group experiencing simulation-based inquiry followed by hands-on experimentation. The study was conducted within the regular science curriculum, and data were collected using validated assessment instruments administered before and after the inquiry activities. All groups addressed the same science topics specified in the national curriculum, and the duration of learning activities was kept equivalent under all conditions. The study was conducted over three weeks during the second semester of the 2025 academic year, comprising a total of eight class sessions structured according to the 5E learning cycle: one session for Engage (Session 1), three sessions for Explore (Sessions 2–4), two sessions for Explain (Sessions 5–6), one session for Elaborate (Session 7), and one session for Evaluate (Session 8). During learning sessions, the learning objectives and assessment tasks remained identical across conditions, while the mode of inquiry activities varied by group. The detailed activity flow for each group was organised in accordance with the 5E phases and is summarised in Table 2.

Table 2
Summary of Science Inquiry Module by 5E Phase and Inquiry Group

Learning Step	Hands-on inquiry group	Simulation inquiry group	Blended inquiry group
Engage	• Checking students’ prior conceptions through teacher questioning • Introducing key terms and basic concepts through teacher guidance	• Using the simulation to identify students’ prior conceptions • Learning key terms and basic concepts through concept explanations provided in the simulation	• Using simulation to examine prior conceptions and related terms • Linking simulation-based concept explanations to real phenomena with concrete materials, when appropriate

Learning Step	Hands-on inquiry group	Simulation inquiry group	Blended inquiry group
Explore	• Manipulating variables using laboratory materials to conduct an inquiry • Recording of observed results during inquiry activities	• Manipulating various variables within the simulation to conduct the inquiry • Conducting repeated experiments by changing conditions	• Conducting an inquiry in the simulation by changing different conditions • Conducting inquiry activities using laboratory materials • Reproducing experimental conditions in the simulation when material or environmental limitations restrict repeated experimentation
Explain	• Organising and explaining concepts based on experimental results • Refining explanations through teacher questions and brief guidance, when needed	• Constructing explanations based on simulation results • Rerunning the simulation to review results when conceptual checking is required	• Explaining concepts by comparing and integrating experimental and simulation results • Refining explanations using information from both sources and teacher guidance, when necessary
Elaborate	Applying learned concepts to new situations through common extension activities		
Evaluate	Completing common assessment tasks, including written and performance-based items to verify understanding		

Before and after the inquiry activities, all participants completed three validated instruments: the Test of Science Process Skills (TSPS), Keller's Motivation Scale, and the Task Commitment Inventory in Science Learning. These pre- and post-tests were administered to examine changes in students' inquiry skills and affective characteristics across the three inquiry conditions.

Instruments

Inquiry Ability

The TSPS, developed by Kwon and Kim (1994), was modified and supplemented to examine primary students' science inquiry ability. The TSPS was originally designed for use with students in primary school grades 5 and above. The inquiry ability is divided into basic and integrated inquiry skills. As the inquiry model developed here is based on government textbooks that reflect the Korean national curriculum, a variety of text and picture materials are presented at the primary school level to help students understand. It was deemed appropriate to examine students' scientific inquiry ability using the TSPS, which has been successfully used in previous research targeting Korean primary school students (Hong & Hong, 2019; Park et al., 2017). The TSPS originally included 30 multiple-choice questions, with three items for each sub-element. In this study, one item unfamiliar to primary students was excluded from each of the observation and measurement sub-elements, leaving a total of 28 items. The content validity index (CVI) was obtained and analysed by applying a two-step rating method of appropriate (1) and inappropriate (0), based on the responses of six experts. In finalising the questions, the reliability (Cronbach's α) was found to be .74. A total of 28 points were scored, with 1 point for a correct answer and 0 for an incorrect answer. The examination time was about 40 minutes.

Affective Domain

Two instruments were used to examine the affective characteristics of the students. First, Keller's (2009) Motivation Scale, based on the ARCS model, was used to assess learning motivation on four dimensions: Attention, Relevance, Confidence, and Satisfaction. Each item was rated on a 5-point Likert scale. The internal consistency reliability (Cronbach's α) in the present study was .89. The reliability coefficients for the four subdomains ranged from .88 to .89. Second, student task commitment was measured using the Task Commitment Inventory in Science Learning developed by Kim et al. (2013). The instrument consists of 23 items in five subdomains: persistence, goal-setting, intrinsic motivation, confidence and expectancy, and immersion and concentration. The internal consistency reliability (Cronbach's α) for the present study was .81. The internal consistency reliability coefficients ranged from .79 to .83 in this study.

Data Analysis

Analysis of covariance (ANCOVA) was conducted to examine differences among the three inquiry groups (hands-on, simulation-based, and blended), with pre-test scores included as covariates. The analyses were performed separately for scientific inquiry skills, learning motivation, and task commitment. The effect sizes were reported as partial η^2 , and the statistical significance was set at $\alpha = .05$ (two-tailed). Before conducting ANCOVA, the assumptions of normality, homogeneity of variance, and homogeneity of regression slopes were tested for each dependent variable. Where the omnibus F-test indicated significant group differences, pairwise comparisons were conducted using Bonferroni-adjusted post hoc tests to identify specific group differences. All statistical analyses were conducted with SPSS version 28.

Research Results*Effects on Scientific Inquiry Skills*

When calculating mean scores to examine students' scientific inquiry skills, different patterns of change were observed in the three groups. In the hands-on inquiry group, post-test scores increased in observation, inference, prediction, transforming data, formulating hypotheses, and controlling variables, while classification, interpreting data, and generalisation decreased. In the simulation inquiry group, post-test scores increased in most subskills, including observation, classification, measurement, prediction, transforming data, interpreting data, formulating hypotheses, and controlling variables, while decreases were found in inference and generalisation. In the blended inquiry group, clear increases were found in classification, measurement, prediction, transforming data, interpreting data, formulating hypotheses, and controlling variables, whereas inference showed a slight decrease. The hands-on inquiry group showed relatively small changes in mean subskill scores across most inquiry skills. In particular, the mean observation score increased from 1.65 to 2.00, while classification and generalisation showed slight decreases after the implementation. The simulation inquiry group showed notable increases in the mean scores for transforming data, which increased from 1.21 to 2.00, interpreting data, which increased from 1.76 to 2.06, formulating hypotheses, which increased from 1.18 to 1.97, and controlling variables, which increased from 0.82 to 2.09. The blended inquiry group showed the largest increases in several higher-order inquiry skills. The mean score for transforming the data increased from 1.22 to 2.47, interpreting data from 1.69 to 2.44, formulating hypotheses from 1.33 to 2.75, and controlling variables from 0.81 to 2.22. Classification also increased markedly from 1.22 to 1.89 in the blended inquiry group. In terms of scientific inquiry skills, relatively limited improvement was observed in the hands-on inquiry group, and some subskills, including classification, interpreting data, and generalisation, showed decreases after the inquiry activities.

However, the simulation inquiry group showed a wider improvement in subskills, particularly in transforming data, interpreting data, formulating hypotheses, and controlling variables. The blended inquiry group showed the greatest overall increase in several inquiry skills, especially those related to higher-level reasoning and data processing. Overall, simulation use supported the development of inquiry skills related to data handling and reasoning, and when combined with hands-on activities, the effect was even greater. Table 3 presents the results of an ANCOVA analysis with pre-test scores as covariates to determine whether differences in post-test scientific inquiry skills among the groups were attributable to group effects.

Table 3
Pre-test and Post-test Mean Scores for Scientific Inquiry Skills by Group

Measurement		Hands-on M (SD)	Simulation M (SD)	Blended M (SD)
Observation	Pre	1.65 (0.49)	1.68 (0.53)	1.50 (0.51)
	Post	2.00 (0.00)	1.88 (0.33)	1.72 (0.51)
Classification	Pre	1.65 (0.91)	1.03 (0.87)	1.22 (0.96)
	Post	1.23 (0.88)	1.65 (0.95)	1.89 (0.85)
Measurement	Pre	1.23 (0.76)	1.03 (0.72)	1.08 (0.73)
	Post	1.23 (0.67)	1.24 (0.65)	1.25 (0.69)

Measurement		Hands-on <i>M (SD)</i>	Simulation <i>M (SD)</i>	Blended <i>M (SD)</i>
Inference	Pre	1.87 (0.88)	1.79 (0.88)	1.69 (0.67)
	Post	1.97 (0.91)	1.88 (0.81)	1.64 (0.68)
Prediction	Pre	2.16 (0.64)	2.06 (0.89)	2.06 (0.86)
	Post	2.26 (0.63)	2.26 (0.75)	2.31 (0.75)
Transforming data	Pre	1.29 (0.69)	1.21 (0.91)	1.22 (0.87)
	Post	1.45 (0.62)	2.00 (0.70)	2.47 (0.51)
Interpreting data	Pre	1.68 (0.54)	1.76 (0.61)	1.69 (0.67)
	Post	1.58 (0.72)	2.06 (0.69)	2.44 (0.61)
Formulating hypotheses	Pre	1.39 (0.67)	1.18 (0.87)	1.33 (0.72)
	Post	1.55 (0.62)	1.97 (0.67)	2.75 (0.50)
Controlling variables	Pre	0.90 (0.70)	0.82 (0.97)	0.81 (0.75)
	Post	1.29 (0.82)	2.09 (0.97)	2.22 (0.76)
Generalisation	Pre	2.13 (0.85)	1.94 (1.01)	2.00 (1.01)
	Post	1.87 (0.92)	1.38 (0.99)	2.06 (1.04)

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group.

A comparison of the mean scores on the scientific inquiry skills test between the three groups showed that the hands-on inquiry group obtained the highest mean scores in observation, although the differences from the simulation-based inquiry group were small. For classification, the blended inquiry group showed the highest mean score, but the difference from the simulation-based inquiry group was also relatively small. In the case of measurement, inference, and prediction, the mean scores of the three groups were nearly identical or showed only slight differences. In general, these results suggest that some subcomponents commonly considered basic science process skills showed relatively higher post-test scores in the hands-on inquiry group (Table 4). However, it was necessary to determine whether these mean differences were statistically significant. Consequently, ANCOVA was conducted using pre-test scores as covariates, followed by Bonferroni-adjusted post hoc comparisons to examine pairwise group differences.

Table 4

Adjusted Post-test Means and ANCOVA Results for Students' Inquiry Skills by Group

Measurement	Hands-on EMM (SE)	Simulation EMM (SE)	Blended EMM (SE)	<i>F</i> (2, 97)	<i>p</i>	Partial η^2
Observation	2.00 (0.06) a	1.88 (0.06) ab	1.73 (0.06) b	4.57	.013	.086
Classification	1.23 (0.17) a	1.65 (0.16) ab	1.89 (0.15) b	4.36	.015	.082
Measurement	1.21 (0.12) a	1.25 (0.12) a	1.25 (0.11) a	.03	.966	.001
Inference	1.97 (0.14) a	1.88 (0.14) a	1.64 (0.13) a	1.48	.233	.030
Prediction	2.23 (0.12) a	2.28 (0.11) a	2.32 (0.11) a	.15	.865	.003
Transforming data	1.45 (0.11) a	2.00 (0.11) b	2.47 (0.10) c	23.00	<.001	.322
Interpreting data	1.59 (0.12) a	2.05 (0.12) b	2.45 (0.11) c	13.75	<.001	.221
Formulating hypotheses	1.55 (0.11) a	1.97 (0.10) b	2.75 (0.10) c	34.55	<.001	.416
Controlling variables	1.29 (0.15) a	2.09 (0.15) b	2.22 (0.14) b	11.24	<.001	.188
Generalisation	1.84 (0.17) a	1.40 (0.16) a	2.06 (0.16) b	4.22	.017	.080

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group, EMM = estimated marginal mean; values in parentheses are standard errors. EMMs are adjusted for pre-test scores used as covariates in the ANCOVA and may therefore differ from the raw means reported in Table 3. Means sharing the same superscript letter are not significantly different at $p < .05$ (Bonferroni-adjusted). Statistically significant effects are indicated in bold.

As shown in Table 4, statistically significant group effects were found for basic and integrated inquiry skills on the scientific inquiry skills test. Among basic inquiry skills, significant group differences were found for observation, $F(2, 97) = 4.57, p = .013$, partial $\eta^2 = .086$, and classification, $F(2, 97) = 4.36, p = .015$, partial $\eta^2 = .082$. In contrast, no statistically significant group differences were found for measurement, $F(2, 97) = 0.03, p = .966$, partial $\eta^2 = .001$; inference, $F(2, 97) = 1.48, p = .233$, partial $\eta^2 = .030$; and prediction, $F(2, 97) = 0.15, p = .865$, partial $\eta^2 = .003$. Among the integrated inquiry skills, statistically significant group effects were found for transforming data, $F(2, 97) = 23.00, p < .001$, partial $\eta^2 = .322$; interpreting data, $F(2, 97) = 13.75, p < .001$, partial $\eta^2 = .221$; formulating hypotheses, $F(2, 97) = 34.55, p < .001$, partial $\eta^2 = .416$; controlling variables, $F(2, 97) = 11.24, p < .001$, partial $\eta^2 = .188$; and generalisation, $F(2, 97) = 4.22, p = .017$, partial $\eta^2 = .080$. Significant group effects were observed for observation and classification, with medium effect sizes, and for transforming data, interpreting data, formulating hypotheses, and controlling variables, with large effect sizes.

Post hoc comparisons indicated that for observation, the hands-on inquiry group scored significantly higher than the blended inquiry group, whereas the simulation group did not differ significantly from either group. A similar pattern was found for classification, in which the blended inquiry group scored significantly higher than the hands-on inquiry group, while the simulation group did not differ significantly from either group. No significant post hoc differences were found for measurement, inference, or prediction. For transforming data, interpreting data, and formulating hypotheses, all three groups differed significantly from each other, the blended inquiry group showing the highest scores, followed by the simulation group and the hands-on inquiry group. For controlling variables, both the simulation and blended inquiry groups scored significantly higher than the hands-on inquiry group, whereas the difference between the simulation and blended inquiry groups was not statistically significant. For generalisation, the blended inquiry group scored significantly higher than both the hands-on and simulation inquiry groups, while no significant differences were found between the hands-on and simulation inquiry groups.

Effects on Learning Motivation

Table 5 presents the mean scores for the pre-test and post-test for the students' motivation in the three groups. In the hands-on inquiry group, the mean motivation score slightly decreased from 124.19 in the pre-test to 122.55 in the post-test. In contrast, the simulation inquiry group showed an increase from 126.76 to 134.29, while the blended inquiry group showed the largest increase, from 129.31 to 137.83. Overall, motivation increased substantially in both the simulation and blended inquiry groups compared to the hands-on inquiry group. To examine these patterns in greater detail, changes in each motivational subdomain were also analysed.

Table 5
Pre-test and Post-test Mean Scores for Motivation by Group

Measure		Hands-on M (SD)	Simulation M (SD)	Blended M (SD)
Motivation	Pre	124.19 (18.51)	126.76 (15.61)	129.31 (13.43)
	Post	122.55 (20.35)	134.29 (18.49)	137.83 (17.54)
Attention	Pre	42.26 (10.02)	42.85 (5.36)	42.08 (6.93)
	Post	40.61 (6.77)	44.50 (6.58)	46.00 (6.08)
Relevance	Pre	31.19 (4.96)	31.29 (4.42)	31.89 (4.70)
	Post	31.13 (6.00)	34.00 (5.29)	34.58 (4.40)
Confidence	Pre	30.48 (5.38)	31.09 (4.42)	32.81 (4.33)
	Post	30.06 (4.30)	32.00 (5.16)	33.11 (4.81)
Satisfaction	Pre	20.26 (4.73)	21.53 (3.69)	22.53 (4.41)
	Post	20.74 (5.55)	23.79 (4.07)	24.14 (3.91)

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group.

In the hands-on inquiry group, attention decreased slightly, whereas the other motivational subdomains showed minimal change. In the simulation inquiry group, attention increased by 1.65 points, relevance by 2.71 points, and satisfaction by 2.26 points. Similarly, in the blended inquiry group, attention increased by 3.92 points,

relevance by 2.69 points, and satisfaction by 1.61 points. In contrast, confidence showed relatively little change between the groups, although the simulation inquiry group demonstrated slightly greater improvement than the other groups. In the change in motivation for scientific inquiry activities, little change was observed in the hands-on group, and a slight decrease in attention was observed. However, the amount of change in the attention factors was highest in the blended groups, followed by the simulation group, and the amount of change in satisfaction was highest in the order of simulation group and blended group. In other words, when the simulation was used, attention levels increased, and when it was used alongside the hands-on activity, the increase was even greater. Table 6 presents the results of an ANCOVA analysis using pre-test scores as a covariate to confirm whether the change in motivation for scientific inquiry activities across groups is due to the group effect.

Table 6*Adjusted Post-test Means and ANCOVA Results for Learning Motivation by Group*

Measure	Hands-on EMM (SE)	Simulation EMM (SE)	Blended EMM (SE)	<i>F</i> (2, 97)	<i>p</i>	Partial η^2
Motivation	123.93 (3.07) a	134.35 (2.91) b	136.59 (2.84) b	5.06	.008	.095
Attention	40.63 (1.15) a	44.43 (1.10) ab	46.05 (1.07) b	6.18	.003	.110
Relevance	31.26 (0.86) a	34.09 (0.82) ab	34.39 (0.79) b	4.24	.017	.080
Confidence	30.63 (0.74) a	32.23 (0.70) a	32.41 (0.69) a	1.85	.163	.037
Satisfaction	21.25 (0.76) a	23.78 (0.72) a	23.72 (0.71) a	3.68	.029	.071

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group, EMM = estimated marginal mean; values in parentheses are standard errors. Means sharing the same superscript letter are not significantly different at $p < .05$ (Bonferroni-adjusted). Statistically significant effects are indicated in bold. EMMs are adjusted for pre-test scores used as covariates in the ANCOVA and may therefore differ from the raw means reported in Table 5.

Significant differences were observed between the three inquiry groups in motivation for the science inquiry activity, $F(2, 97) = 5.06, p = .008$, partial $\eta^2 = .095$. In other words, depending on the type of inquiry class, the effect of the learning motivation of the students differed between the groups. To identify the sub-factors that contributed to this group difference, the pre-test results for each sub-factor were analysed as covariates, and statistically significant group effects were identified. Statistically significant group effects were found for several motivational subdomains. For attention, a significant group effect was observed, $F(2, 97) = 6.18, p = .003$, partial $\eta^2 = .110$, with the blended inquiry group scoring significantly higher than the hands-on inquiry group, whereas the simulation inquiry group did not differ significantly from either group. A similar pattern for relevance was found, $F(2, 97) = 4.24, p = .017$, partial $\eta^2 = .080$. Post hoc comparisons indicated that the blended inquiry group scored significantly higher than the hands-on inquiry group, whereas the simulation inquiry group did not differ significantly from either group. Furthermore, the satisfaction level was significant, $F(2, 97) = 3.68, p = .029$, partial $\eta^2 = .071$, indicating small group effects, but the group difference was not clearly distinguished in the Bonferroni test. In contrast, no significant group effects were found for confidence, $F(2, 97) = 1.85, p = .163$, partial $\eta^2 = .037$. These results suggest that the way simulation content is incorporated into science class can produce different effects on students' learning motivation. In addition, the effects may differ across sub-factors of motivation depending on the type of science inquiry class.

Effects on Task Commitment

Table 7 presents the mean scores of the pre-test and post-test for the students' task commitment in the three groups. In the hands-on inquiry group, the mean task commitment score increased from 80.19 at the pre-test to 88.42 at the post-test. The simulation inquiry group also showed an increase, from 84.26 to 92.68. The blended inquiry group demonstrated the largest increase, with scores rising from 83.25 at pre-test to 103.03 at post-test. In terms of overall score changes, the hands-on inquiry group increased by 8.23 points, the simulation inquiry group by 8.42 points, and the blended inquiry group by 19.78 points. To examine these differences in greater detail, changes in each task commitment subdomain were also analysed.

Table 7
Pre-test and Post-test Mean Scores for Task Commitment by Group

Measure		Hands-on <i>M (SD)</i>	Simulation <i>M (SD)</i>	Blended <i>M (SD)</i>
Task commitment	Pre	80.19 (9.55)	84.26 (11.43)	83.25 (8.34)
	Post	88.42 (11.76)	92.68 (12.58)	103.03 (7.62)
Persistence	Pre	13.52 (2.67)	14.65 (2.65)	15.31 (2.64)
	Post	13.84 (2.84)	15.21 (3.24)	15.75 (2.16)
Goal-setting	Pre	21.45 (3.49)	23.12 (4.20)	22.17 (2.89)
	Post	24.39 (4.07)	25.62 (3.91)	28.08 (3.03)
Intrinsic motivation	Pre	15.52 (2.80)	16.15 (2.43)	15.31 (1.77)
	Post	19.16 (2.50)	20.82 (1.75)	21.19 (2.29)
Confidence & expectancy	Pre	17.35 (2.42)	17.53 (2.92)	18.14 (2.38)
	Post	18.29 (3.32)	18.26 (3.41)	19.67 (2.15)
Immersion & concentration	Pre	12.35 (1.14)	12.82 (2.77)	12.33 (1.82)
	Post	12.74 (1.90)	12.76 (2.66)	18.33 (1.22)

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group.

For persistence, confidence, and expectancy, little change was observed between the three groups. In contrast, the blended inquiry group showed substantially greater improvement in goal-setting, with an increase of 5.91 points, which was more than twice the increase observed in the hands-on and simulation inquiry groups. For intrinsic motivation, the magnitude of improvement increased progressively from the hands-on inquiry group to the simulation inquiry group and was highest in the blended inquiry group. A similar pattern was observed for immersion and concentration. Whereas the hands-on and simulation inquiry groups showed minimal change, the blended inquiry group demonstrated a marked increase of 6.00 points. In general, the blended inquiry condition was associated with greater improvements in goal-setting, immersion, and concentration, while intrinsic motivation showed more positive changes in the simulation and blended inquiry groups than in the hands-on inquiry group. Table 8 presents the ANCOVA results using pre-test scores as covariates.

Table 8
Adjusted Post-test Means and ANCOVA Results for Task Commitment by Group

Measure	Hands-on <i>EMM (SE)</i>	Simulation <i>EMM (SE)</i>	Blended <i>EMM (SE)</i>	<i>F(2, 97)</i>	<i>p</i>	Partial η^2
Task commitment	89.76 (1.71) a	91.80 (1.62) a	102.70 (1.57) b	18.73	<.001	.280
Persistence	14.45 (0.42) a	15.14 (0.39) a	15.75 (0.39) a	1.17	.314	.024
Goal-setting	24.66 (0.63) a	25.33 (0.61) a	28.12 (0.58) b	9.46	<.001	.163
Intrinsic motivation	19.19 (0.39) a	20.72 (0.37) b	21.27 (0.36) b	8.20	.001	.145
Confidence & expectancy	18.49 (0.47) a	18.36 (0.45) a	19.41 (0.44) a	1.67	.194	.033
Immersion & concentration	12.75 (0.36) a	12.74 (0.35) a	18.35 (0.34) b	89.62	<.001	.649

Note. Hands-on = Hands-on inquiry group, Simulation = Simulation inquiry group, Blended = Blended inquiry group, EMM = estimated marginal mean; values in parentheses are standard errors. Means sharing the same superscript letter are not significantly different at $p < .05$ (Bonferroni-adjusted). Statistically significant effects are indicated in bold. EMMs are adjusted for pre-test scores used as covariates in the ANCOVA and may therefore differ from the raw means reported in Table 7.

As shown in Table 8, significant group effects were found for overall task commitment, $F(2, 97) = 18.73$, $p < .001$, partial $\eta^2 = .280$. Bonferroni-adjusted pairwise comparisons indicated that the blended inquiry group scored significantly higher than both the hands-on and simulation inquiry groups, whereas no significant differences were found between the hands-on and simulation inquiry groups. For the task commitment subdomains, significant group effects were found for goal-setting, $F(2, 97) = 9.46$, $p < .001$, partial $\eta^2 = .163$; intrinsic motivation,

$F(2, 97) = 8.20, p = .001$, partial $\eta^2 = .145$; and immersion and concentration, $F(2, 97) = 89.62, p < .001$, partial $\eta^2 = .649$. Post hoc comparisons showed that the blended inquiry group scored significantly higher than both the hands-on and simulation inquiry groups in goal-setting, immersion, and concentration. For intrinsic motivation, both the simulation and blended inquiry groups scored significantly higher than the hands-on inquiry group, whereas no significant differences were found between the simulation and blended inquiry groups. In contrast, no significant group effects were found for persistence, $F(2, 97) = 1.17, p = .314$, partial $\eta^2 = .024$, or confidence and expectancy, $F(2, 97) = 1.67, p = .194$, partial $\eta^2 = .033$.

Discussion

Scientific inquiry skills are central objectives of primary science education, since they are closely related to the students' ability to reason scientifically and solve problems through inquiry. However, a single inquiry approach may not address both the procedural and conceptual demands of scientific inquiry. Hands-on inquiry directly provides experiential learning, while simulation-based inquiry offers visualisation, manipulation, and repeated exploration for scientific inquiry learning. On the other hand, reliance on a single inquiry approach has intrinsic advantages and limitations. The limitations of a single approach can also be complemented by integrating different inquiry approaches. In this context, simulation-based inquiry can be most effective when used to complement rather than replace hands-on inquiry. Significant group differences were found in transforming data, interpreting data, formulating hypotheses, and controlling variables. These skills require students to coordinate conceptual understanding with procedural reasoning.

The positive effect of inquiry skills in both the simulation and blended inquiry groups suggests that an interactive learning environment integrating variable manipulation can effectively support the development of scientific reasoning. Students can easily manipulate variables and observe immediate outcomes in a simulation-based environment, and it can help refine their causal reasoning and develop their hypothesis-generating ability. However, depending on only simulation-based learning environments can increase cognitive demands when learners are required to engage in complex skill processing during experimental activities (Chernikova et al., 2020). The sequential inquiry structure allowed students to focus on different inquiry processes at different stages rather than performing all cognitive tasks simultaneously. In this study, the blended inquiry condition may have reduced excessive cognitive demands by separating and organising initial exploration using simulation from hands-on experimentation.

Students first explored variables and identified patterns through simulations, and they tested and confirmed their ideas with physical experiments. The reduction of cognitive overload during the inquiry process may explain the greater improvement of the blended inquiry group in higher-order inquiry skills, particularly transforming data, formulating hypotheses, and controlling variables. In other words, the blended inquiry condition, which sequentially incorporated simulation-based inquiry and hands-on experiments, appears to have distributed cognitive processing across different stages of inquiry, rather than simply applying simulation content to science learning. Therefore, the result of this study is connected with research showing that structured scaffolding in digital environments helps learners manage inquiry tasks more effectively (Al Mamun & Lawrie, 2024; Hofer & Reinhold, 2025). These cognitive improvements appear to be related to the observed improvements in the affective domain, particularly in attention and satisfaction. The use of simulations in primary science classes provides effects similar to those reported in previous studies, which have shown that dynamic representations, interactive manipulation, and immediate feedback can support attentional engagement (Banda & Nzababimana, 2021; Rahmawati et al., 2022).

In the blended condition, students not only explored phenomena virtually but also verified their findings with real materials. This process may have made the inquiry more concrete and meaningful. It may also help explain the higher attention in the blended inquiry group and the positive pattern of satisfaction in the simulation and blended groups. Simulation-based interactive learning environments have been associated with high levels of student engagement and satisfaction and have been known to enhance affective learning outcomes, such as motivation and interest in science education (Almasri, 2022; Koç & Kanadlı, 2025). From this perspective, the integration of simulation and hands-on experiments may have enhanced the students' sense of achievement by allowing them to confirm virtual explorations through real-world activities.

A similar explanation may also apply to task commitment. The blended inquiry group showed greater improvement in overall task commitment, especially in goal-setting, immersion, and concentration. These results are related to previous research (Wörner et al., 2022), which found complementary advantages of interactive simulation and tangible experimentation. In this study, by allowing learners to benefit from both dynamic, manipulable representations and concrete, physical experiences, the blended approach may have supported sustained engagement across different phases of inquiry. In particular, the simulation provided students with a clear starting point for inquiry, and

the hands-on activity gave them a concrete goal to test. This continuity between virtual exploration and hands-on verification may have made the inquiry task more purposeful and manageable for primary students.

Both the simulation and blended inquiry groups also showed higher levels of intrinsic motivation than the hands-on inquiry group. This result is consistent with previous research showing that interactive virtual laboratory environments can positively influence motivation (Diwakar et al., 2023). In this study, simulation use may have supported intrinsic motivation by allowing students to repeat trials, manipulate conditions, and observe changes directly. When this experience was followed by hands-on experimentation, students could connect virtual results with real phenomena, which may have promoted more active engagement and sustained immersion in the inquiry process.

By contrast, persistence, confidence, and expectancy did not show the same pattern: these subdomains may be less sensitive to short-term instructional interventions. They may reflect relatively stable learner characteristics shaped by prior learning experiences. In particular, expectancy-related beliefs tend to develop gradually through accumulated experiences rather than being easily changed by brief educational activities (Bandura, 1997). This may explain why the inquiry condition had limited effects on persistence, confidence, and expectancy.

At the same time, hands-on inquiry retained educational value. For observation, a basic inquiry skill, the hands-on inquiry group scored significantly higher than the blended inquiry group. The simulation group did not differ significantly from either group. Although inference and prediction did not show statistically significant group differences, the mean scores for these subskills were numerically comparable or slightly higher in the hands-on inquiry group. Direct experimentation therefore remains important for foundational inquiry processes that depend on sensory experience with real-world phenomena.

For primary science education, these findings point to the need for intentional sequencing of digital and physical inquiry activities. Integrating simulation-based inquiry with hands-on experimentation can provide a more balanced learning environment. Whereas simulations support variable manipulation, repeated trials, and pattern identification, hands-on experiments provide sensory experience and physical verification. When the two are used in a structured sequence, students may be better able to manage the cognitive and affective demands of inquiry. Blended inquiry can therefore support higher-order inquiry skills while also sustaining engagement in science learning.

Conclusions and Implications

This study produced three principal findings regarding the effects of different inquiry approaches in primary science education. First, simulation-based and blended inquiry both strengthened higher-order skills that depend on systematic reasoning, namely transforming data, interpreting data, formulating hypotheses, and controlling variables. Second, working with simulations enhanced students' affective outcomes, including intrinsic motivation, goal-setting, and attention. Third, experiencing both simulation-based activities and hands-on experimentation in sequence was especially effective for inquiry skills and affective outcomes, indicating that blended inquiry provides a structured environment for sustained participation and higher-order reasoning.

The pattern suggests that simulations support systematic reasoning by allowing students to manipulate variables interactively, while blended inquiry adds value by distributing cognitive demands across inquiry phases and keeping students engaged. However, persistence and confidence-related constructs showed no group differences, which implies that these dispositions respond little to a short implementation. Hands-on inquiry, for its part, remained valuable for foundational skills and for the more stable affective characteristics. In a practical context, the implication is not that simulations should replace physical experiments but that they should work as cognitive scaffolding within the sequential integration of simulation-based and hands-on inquiry emphasised in this study. Designing sequentially to combine simulation-based activities with hands-on experimentation provides an effective approach to enhancing inquiry skills and sustaining engagement in primary science education. Although this study was conducted in Korea, the results are relevant to science educators in other educational systems that are integrating digital inquiry tools into their classrooms.

The contribution of this study is to shift the question from whether simulations outperform hands-on experiments to how the two can be combined. In primary education, teachers are often generalists with limited time and resources; this perspective holds practical significance. The simulation module developed in this study incorporated embedded scaffolding and feedback, enabling teachers to focus more on facilitation. Implementing the simulation prior to the physical experiment allowed students to generate predictions to test with real material, which appeared to support goal-setting and sustained engagement. These findings indicate that blended inquiry is not simply an optional addition but a means of redistributing the demands of inquiry between digital tools and teachers.

Several recommendations follow for primary science practice. Simulations are most effective when used as a complementary tool with hands-on practice rather than as a replacement, since direct observation and other sensory-based skills continue to depend on physical experimentation. The sequencing of simulation and hands-on activities is a critical design consideration; implementing structured simulations prior to experiments provides a practical approach to fostering higher-order inquiry in typical classrooms when materials or time run short. Web-based simulations, which do not require specialised equipment, can lower barriers to inquiry in under-resourced schools and may help reduce the educational gap between schools with varying resources. Achieving these benefits depends on adequate teacher preparation. Therefore, curriculum guides and professional development should treat blended inquiry as an intentional teaching design rather than as an occasional use of digital tools.

However, these findings should be interpreted with caution, since the implementation was short and covered only two inquiry topics, which may have limited the extent to which changes in the more stable constructs could be detected. In addition, the study relied on paper-and-pencil instruments to assess scientific inquiry skills, learning motivation, and commitment to tasks. Although these instruments were validated and showed acceptable reliability, they may not fully capture the actual inquiry performance or classroom engagement of the students. Because the study was conducted with sixth-grade students from a single primary school in Korea, the generalisability of the findings to other grade levels, school contexts, or educational systems may be limited. Furthermore, the design relied on intact classes, and classroom-level factors such as teacher effects and class climate may also have influenced the results despite the use of pre-test covariates. Future studies should include a wider range of inquiry topics, diverse educational settings, and longer implementation periods to examine whether these findings can be generalised across different learning contexts.

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Declaration of Interest

The authors declare no competing interest.

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