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Developing and Applying Primary Students' Scientific Method Skills through a STEM Intervention: A Convergent Mixed-Methods Study

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Abstract

This study examined the development of scientific method skills in fifth- and sixth-grade primary school students within the context of a STEM-based instructional intervention. A convergent mixed-methods approach was employed, combining quantitative data from questionnaires and qualitative data from semi-structured interviews, with a sample of 110 students aged 10-12. The results showed that students were able to recognize key scientific processes at high rates, particularly those related to hands-on activities, such as observation, experimentation, and measurement. However, their ability to recall and apply these processes independently was more limited. Students performed better in more practical processes (observation, measurements), while they experienced difficulties in processes that required thinking, such as formulating hypotheses, experimental design, and drawing conclusions. In addition, students evaluated hands-on processes as more helpful for understanding scientific concepts, while processes involving reasoning and interpretation were perceived as less influential. Several misconceptions were also identified, including confusion between observation and measurement and difficulties in evidence-based reasoning. Overall, the findings suggest that students have developed a functional but not yet fully consolidated understanding of scientific method.

Keywords: scientific method, scientific skills, mixed methods, STEM education, primary education

1. Introduction

1.1 The Challenge of Developing Scientific Method Skills in Primary Education

The development of scientifically literate citizens is a central goal of contemporary science education, as it supports individuals' ability to understand, evaluate, and use scientific knowledge in everyday decision-making (J. Lederman et al., 2025; OECD, 2019). However, research shows that students often demonstrate limited understanding and application of scientific method procedures (J. S. Lederman et al., 2019, 2021). In many educational contexts, including Greece, science teaching remains largely content-focused and teacher-centered, with limited emphasis on inquiry, experimentation, and the systematic development of scientific reasoning skills (Gikopoulou, 2017; Kotsis et al., 2025; Sideri & Skoumios, 2021).

Scientific method is not simply a sequence of steps, but a structured and dynamic process that includes observation, hypothesis formulation, experimentation, data analysis, and conclusion drawing, functioning as a mechanism for constructing scientific knowledge (Attrassi, 2021; Kolodner et al., 2003). Within education, the development of these processes remains challenging, as students often tend to confuse observation with mere seeing or interpretation, fail to recognize measurement as an objective process of data collection and exhibit difficulties in controlling variables, and in applying evidence-based reasoning (Griffiths & Thompson, 1993; Ayuso Fernández et al., 2022). In response to these challenges, this study explores the contribution of a STEM-based teaching intervention to the development of students' scientific method skills, their assessment of the role of individual processes in understanding science concepts, and the difficulties they face when applying them in the context of speed and photovoltaic systems.

For the interpretation of the learning process, the present study adopts Cultural-Historical Activity Theory (CHAT), which conceptualizes learning as a socially mediated and goal-oriented activity (Engeström, 1987, 2015). Within this framework, students participate in activity systems where knowledge is constructed through the interaction between the subject and both material tools (STEM materials, experimental setups) and cognitive tools (scientific method processes)(Cole, 1996; Engeström, 2015), as well as the community and the object of the activity. Scientific inquiry can thus be understood as a collective and mediated practice, in which the processes of the scientific method function as tools for thinking and action. Furthermore, students' difficulties and misconceptions can be interpreted as manifestations of contradictions within the activity system, understood as inherent, systemic tensions that drive transformation and development (Engeström, 2001; Foot & Groleau, 2011), thereby promoting the learning process and the gradual reorganization of knowledge.

1.2 Theoretical Framework: CHAT and Scientific Inquiry

The development of processes such as observation, questioning, experimentation, and drawing conclusions from an early age can be associated with the development of scientific literacy. This is supported by the findings of Leonia et al. (2025), which suggest that scientific literacy encompasses scientific thinking and is fostered through active, inquiry-based learning experiences. Furthermore, engagement in scientific inquiry processes contributes to the development of scientific competencies and has been linked to critical thinking and informed citizenship (Pereira et al., 2020).

Within this context, STEM education has been proposed as an effective instructional framework, as it promotes inquiry-based learning, experimentation, and problem-solving, leading to improvements in students' science knowledge and skills (Apaivatin et al., 2021; Cotabish et al., 2013; Sari et al., 2020).

More specifically, research indicates that STEM education enhances a wide range of science process skills, including observing, hypothesizing, experimenting, and drawing conclusions, which are considered fundamental components of scientific literacy (Apaivatin et al., 2021; Kaewmanee et al., 2024). In addition, empirical studies have demonstrated that participation in STEM programs results in statistically significant improvements in students' science process skills, conceptual understanding, and content knowledge (Cotabish et al., 2013; Sari et al., 2020). These improvements are largely attributed to the inquiry-based and problem-centered nature of STEM learning environments, where students actively engage in real-world problem solving, experimentation, and engineering design processes (Cotabish et al., 2013; Sari et al., 2020). Consequently, STEM education not only strengthens students' scientific knowledge but also supports the development of higher-order thinking skills, such as critical thinking, creativity, and problem solving (Sari et al., 2020).

1.3 Literature Review in Scientific Method

Research has consistently shown that students encounter significant difficulties in understanding and applying the processes of scientific methods. Students often struggle to formulate scientific hypotheses as testable statements, tending instead to express simple predictions without causal justification (Ayuso Fernández et al., 2022; Guisasola et al., 2006; Park, 2006; Strode, 2020). Difficulties are also evident in experimental design, especially in controlling variables and constructing systematic comparisons, indicating a limited understanding of the logic of controlled experimentation (Griffiths & Thompson, 1993; Kharatmal & Bhattacharya, 2025; M. Schwichow et al., 2022; M. G. Schwichow et al., 2016; Temiz & Tan, 2009).

Students hold several persistent misconceptions about the scientific method, often viewing it as a fixed, linear sequence of steps rather than a flexible and context-dependent process. They frequently misinterpret what constitutes an experiment, assuming that all investigations are experimental, and show confusion between data and evidence, treating them as identical (N. G. Lederman & Lederman, 2019). Additionally, students struggle with data analysis, failing to connect it to answering research questions, and tend to believe that scientists should reach the same conclusions from the same data, attributing differences to errors rather than interpretation (N. G. Lederman & Lederman, 2019). Furthermore, students tend to misinterpret scientific observation as mere visual perception or even as the interpretation of phenomena, while also failing to recognize measurement as a distinct, objective, and systematic process of collecting quantitative data, often conflating it with general or subjective forms of observation (Griffiths & Thompson, 1993).

Overall, these findings suggest that students tend to develop a fragmented and procedural understanding of scientific methods, highlighting the need for instructional approaches that explicitly support the integration and application of scientific processes.

1.4 Research Questions

Based on the above considerations, the present study aims to investigate the contribution of a STEM-based instructional intervention to the development of primary students' scientific method skills, as well as the perceived contribution of individual scientific processes to their conceptual understanding.

The study addresses the following research questions:

RQ1: To what extent do students demonstrate recognition and application of scientific method processes.

RQ2: How do students evaluate the contribution of individual scientific processes to their understanding of the concepts of speed and photovoltaics?

RQ3: What difficulties do students exhibit when applying scientific method processes, and how are these interpreted through qualitative interview data?

2. Method

This study employed a post-intervention convergent mixed methods design (Battista & Torre, 2023; Creswell & Creswell, 2019) to investigate the development of scientific method skills in primary school students. The sample consisted of 110 students from grades 5 and 6 (ages 10-12), selected through convenience sampling. Data were collected using structured questionnaires and semi-structured interviews. Quantitative data were analyzed using both descriptive and inferential statistics, while qualitative data were examined through thematic analysis.

Both data strands were collected concurrently, analyzed separately, and integrated during the interpretation phase. Quantitative findings provided an overview of students' recognition and evaluation of scientific processes, whereas qualitative data offered deeper insights into their reasoning, understanding, and misconceptions. This integration enabled a more comprehensive interpretation of students' learning, capturing both the extent and the nature of their development in scientific method skills.

2.1 Participants

The participants of the study were 110 primary school students enrolled in the 5th and 6th grades (ages 10-12 years). The sample was drawn from four public primary schools located in the region of Ioannina, Greece, representing diverse geographical and socio-cultural backgrounds.

Participation in the study was based on convenience sampling, as the researcher was also the Information and Communication Technologies (ICT) teacher of the participating classes. All students who attended the selected classes during the intervention period were included in the study, ensuring a natural classroom setting and authentic learning conditions.

Both male and female students participated in the research. No exclusion criteria were applied, as the study aimed to capture a representative picture of typical primary school classrooms. Prior to data collection, appropriate permissions were obtained from school authorities, and ethical considerations regarding student participation and data confidentiality were strictly followed.

2.2 Sampling Procedures

A non-probability convenience sampling strategy was employed (Cohen et al., 2007; Creswell, 2012). Participants were recruited from classrooms in four public primary schools in the region of Ioannina, Greece, where the researcher served as the Information and Communication Technologies (ICT) teacher. All students enrolled in the selected 5th and 6th grade classes during the intervention period were invited to participate, and inclusion in the study was based on regular classroom attendance.

Data were collected in the natural school setting during scheduled ICT lessons (one hour per week). The study was implemented as part of regular instructional activities, and no financial or other incentives were provided for participation. The response rate was effectively 100%, as all students present during the administration of the instruments completed the questionnaires.

Appropriate permissions were obtained from school authorities prior to data collection, and ethical standards for research involving minors were observed. Participation was voluntary, and students' responses were anonymized through the use of identification codes.

2.3 Measures and Instruments

Data were collected using a combination of quantitative and qualitative instruments designed to capture students' attitudes toward science, their experiences with scientific activities, and their development of scientific method skills following the intervention.

Quantitative data were analyzed using the IBM SPSS STATISTICS (version 31.0.0.0), through the calculation of descriptive statistics (frequencies, percentages, means, and standard deviations) and inferential statistical analysis, including Spearman's rank correlation coefficient to examine relationships between variables. Qualitative data from the semi-structured interviews were analyzed using thematic analysis (Braun & Clarke, 2006), following an inductive coding process in which students' responses were segmented into meaningful units, coded, and grouped into broader categories reflecting key aspects of their understanding, difficulties, and misconceptions. To enhance the reliability of the qualitative analysis, categories were reviewed iteratively to ensure consistency, while the interpretation of the data were supported by representative excerpts from students' responses. Additionally, the integration of quantitative and qualitative data contributed to the validity of the findings.

2.3.1 Quantitative Measures

The questionnaire focused on students' understanding and application of scientific method and included:

1) self-reported familiarity with how scientists work (question G1),
2) identification and recognition of key scientific processes (question G3),
3) students' beliefs about the reliability of the scientific method (question G4),
4) students' evaluation of the contribution of each scientific process to their understanding of the concepts of speed and photovoltaics, measured through Likert-scale items (question G5),
5) application of scientific method through multiple-choice items targeting specific processes (questions G6a-G6e)

2.3.2 Qualitative Measures

To complement the quantitative data, semi-structured interviews were conducted with a subset of students following the intervention. The interviews aimed to explore in greater depth students' understanding of scientific method, their reasoning when engaging in scientific processes, and the difficulties or misconceptions they encountered. Interview questions focused on: (a) the steps students followed during experiments, (b) their interpretation of key processes such as hypothesis, observation, and measurement, and (c) their reasoning when drawing conclusions from experimental data.

2.3.3 Data Quality and Reliability Considerations

Data were collected only after the completion of the intervention. The instruments included multiple-choice items and Likert-scale questions, measured on a five-point scale (1-5), designed to capture different dimensions of students' understanding of scientific method processes. Specifically, multiple-choice questions were used both to record the processes students reported using during the STEM activities and to assess their conceptual understanding of each process individually. In addition, Likert-scale items were employed to evaluate the extent to which each scientific process contributed to students' understanding of the concepts of speed and photovoltaics. The internal consistency of the Likert-scale items was found to be satisfactory (Cronbach's $\alpha = 0.760$), indicating an acceptable level of reliability. The interpretation of the findings was based on the complementary use of quantitative and qualitative data, allowing for a more comprehensive understanding of students' learning and reasoning.

2.4 Research Design

The present study employed a convergent mixed-methods research design, in which quantitative and qualitative data were collected during the same phase of the research process, analyzed separately, and then integrated to provide a comprehensive understanding of students' development of scientific method skills.

From a quantitative perspective, the study followed a post intervention design without a control group and aimed to examine the development of students' knowledge, skills, and attitudes after implementing a STEM-based instructional intervention. Test data focused on their understanding and application of scientific method processes, as well as their perceived contribution to conceptual learning.

From a qualitative perspective, semi-structured interviews were conducted after the intervention to explore students' reasoning, interpretations, and potential misconceptions regarding scientific processes. These data provided deeper insight into how students understood and applied concepts such as hypothesis formulation, observation, measurement, and conclusion drawing.

The integration of quantitative and qualitative findings followed a convergent approach, where results from both strands were compared and combined during the interpretation phase. This design enhanced the validity of the results.

Overall, the research design aimed to capture not only measurable changes in students' performance but also the underlying cognitive processes and difficulties associated with the development of scientific method skills.

2.5 The STEM Teaching Intervention

The study involved the implementation of a STEM-based instructional intervention designed to engage students in authentic scientific inquiry through hands-on activities and problem-solving tasks. The intervention was integrated into the regular ICT curriculum and was delivered during scheduled class time.

The intervention was structured as a unified program consisting of two thematic modules: (a) the concept of speed and (b) the functioning of photovoltaic systems. In the first module, students explored the concept of speed through experimental activities involving motion, measurement of distance and time, and comparison of results. In the second module, students investigated the operation of photovoltaic systems by constructing simple circuits and examining factors affecting their performance, such as light intensity and environmental conditions.

Across both modules, emphasis was placed on the systematic application of the core processes of scientific method. Students were actively engaged in formulating research questions, developing hypotheses, designing and conducting experiments, making observations, taking measurements using appropriate tools, drawing conclusions based on evidence, and communicating their findings.

The instructional approach was grounded in principles of inquiry-based and experiential learning, encouraging students to participate collaboratively in problem-solving and to reflect on their reasoning processes. The use of hands-on materials and structured experimentation aimed to support the development of a deeper understanding of scientific concepts and practices.

The intervention was implemented over a total duration of approximately eight instructional hours, distributed across the two thematic modules. Efforts were made to ensure consistency in implementation across participating classes, following a common instructional framework and sequence of activities.

In line with Cultural-Historical Activity Theory (CHAT), the intervention was designed as an activity system in which students (subjects) engaged with the object of developing scientific methodology skills through the coordinated use of mediating tools. These tools included both material artifacts (e.g., experimental setups, measurement instruments, STEM materials) and symbolic-cognitive tools (e.g., scientific method processes such as hypothesis formulation, observation, and data interpretation), which structured and supported students' actions. Throughout the activities, students encountered contradictions—such as discrepancies between initial predictions and experimental results or confusion between observation and measurement—which functioned as productive tensions that stimulated reflection, discussion, and conceptual change. Learning was thus conceptualized as a dynamic process of transformation within the activity system, where participation in collaborative inquiry facilitated the gradual internalization of scientific processes as cognitive tools. At the same time, externalization occurred as students articulated their reasoning, tested ideas through experimentation, and constructed observable outcomes. The aim of the intervention is, through this dialectical process of internalization and externalization, supported by mediating tools and guided by contradictions, for students to progressively reorganize their understanding and develop functional skills of scientific methodology.

3. Results

3.1 Participants and Data Collection

Participants were recruited from four public primary schools in the region of Ioannina, Greece. Data collection took place during the regular school timetable, within ICT lessons, over the course of the instructional intervention. All students enrolled in the selected classes participated in test phase of the study.

No participants were excluded from the analysis, and all students who completed the intervention were included in the final dataset. Additionally, a subset of students participated voluntarily in semi-structured interviews conducted after the completion of the intervention.

3.2 Results for Research Question 1

Students recognized several core processes of the scientific method at high rates (Table 1). Specifically, the majority identified measurement (87.3%), hypothesis formulation (81.8%), experimentation (79.1%), drawing conclusions (79.1%), and observation (76.4%) as processes they followed during the experimental activities. These findings suggest that students were able to recognize the main stages of scientific method, particularly those directly associated with hands-on experimentation.

A different pattern emerges in the interview data, where students were asked to recall the processes without predefined options. The most frequently mentioned process was hypothesis

(60.7%), followed by experimentation (57.1%) and observation (53.6%), while measurement (46.4%) and conclusions (50.0%) were mentioned less frequently (Table 1).

The comparison between the two data sources reveals clear differences between recognition and spontaneous recall. Processes such as measurement and conclusion drawing, although highly recognized in the questionnaire, were less frequently recalled in interviews, suggesting that students can identify them when prompted but do not readily retrieve them in unstructured contexts. In contrast, hypothesis formulation and experimentation show more consistent patterns across both data sources, indicating stronger internalization. Observation appears at intermediate levels, suggesting partial but not fully consolidated understanding.

Table 1. Comparison between Recognition (quantitative data) and Recall (qualitative data) of Scientific Method Processes

Scientific Method Process	Quantitative Data (Question G3)	Qualitative Data (Interviews)
Hypothesis	81.8%	60.7%
Experiment	79.1%	57.1%
Observation	76.4%	53.6%
Measurement	87.3%	46.4%
Conclusion	79.1%	50.0%

Overall, the findings indicate that students have developed the ability to recognize key scientific processes; however, their spontaneous recall is more limited and selective. Processes closely associated with active experimentation appear to be more deeply internalized, whereas others are less consistently retrieved.

The following section presents an analysis of quantitative and qualitative data for each scientific process applied within the instructional interventions.

Table 2. Students' Performance in Scientific Method Processes Across Quantitative and Qualitative Data

Scientific Process	Quantitative (Correct Response %)	Qualitative (Correct / Target %)	Key Difficulty
Hypothesis	49.1%	71.4% (causal reasoning)	Difficulty recognizing formal structure
Experiment	60.0%	42.9% (complete design)	Control of variables
Observation	60.0%	71.4%	Confusion with measurement
Measurement	56.4%	85.7%	Use of sensory methods
Conclusion	72.7%	32.1%	Integration of data

Regarding **hypothesis formulation**, the quantitative results indicate that 49.1% of students correctly identified a properly formulated hypothesis, while 27.3% selected responses that included prediction without justification. In contrast, qualitative findings show that 92.9% of students were able to formulate clear predictions and 71.4% provided causal explanations. This indicates a discrepancy between recognition and production, suggesting that students are more capable of verbally expressing hypotheses than identifying their formal structure.

Regarding **experimental design**, 60.0% of students correctly recognized a valid design based on controlling variables, whereas 25.5% selected responses involving multiple changing factors. In the interviews, only 42.9% fully described a correct experimental design, although 53.6% identified the independent variable and 42.9% referred to constants. This suggests that students recognize correct designs more easily than they can independently construct them.

Regarding **scientific observation**, 60.0% of students correctly identified observation as a sensory-based process, while 31.8% confused it with measurement. In contrast, 71.4% of students in the interviews correctly described observation using their senses, although some still confused it with measurement. This indicates that students demonstrate a more functional understanding in open-ended contexts but struggle with conceptual differentiation in structured tasks.

Regarding **measurement**, 56.4% of students correctly identified the use of a thermometer, while 30.0% relied on touch and 8.2% selected inappropriate instruments. In the qualitative data, 85.7% correctly referred to the use of appropriate instruments, although some combined this with sensory approaches. This suggests stronger practical understanding, alongside persistent confusion between observation and measurement.

Finally, regarding **conclusion drawing**, 72.7% of students correctly recognized that conclusions should be based on the comparison of hypotheses, observations, and measurements. However, only 32.1% were able to describe this process correctly in interviews, while others relied on incomplete reasoning or confused it with engineering design processes. This indicates that students can recognize the correct procedure but have difficulty explaining and applying it independently.

Overall, the findings indicate that students developed a basic to moderate level of scientific method skills, with stronger performance in processes related to hands-on experimentation and weaker performance in processes requiring higher levels of abstraction and integration. The comparison between quantitative and qualitative data further reveals that this development is more evident in recognition-based tasks than in open-ended application, suggesting that students' understanding is functional but not yet fully consolidated.

3.3 Results for Research Question 2

As shown in Table 3, students evaluated scientific processes differently in terms of their contribution to conceptual understanding. Processes directly associated with hands-on engagement were rated highest. Observation received the highest mean score (M = 4.09), followed by experimentation (M = 3.93) and measurement (M = 3.87), indicating that students perceived these processes as the most effective for understanding the concepts studied.

Table 3. Students' Evaluation of the Contribution of Scientific Method Processes to Conceptual Understanding

Scientific Process	Mean (M)	Std. Deviation (SD)
Observation	4.09	0.953
Experiment	3.93	0.983
Measurement	3.87	0.940
Conclusion	3.75	1.068
Hypothesis	3.44	1.000

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In contrast, processes that involve higher levels of abstraction and reflection were rated lower. Conclusion drawing (M = 3.75) and hypothesis formulation (M = 3.44) were evaluated as moderately helpful. Additionally, the higher standard deviations observed in these processes suggest greater variability in students' perceptions of their usefulness.

The findings indicate that students perceive scientific processes as contributing to learning primarily when they involve direct interaction with experimental phenomena. Conversely, processes related to reasoning and interpretation are perceived as less influential. Therefore, the development of understanding is reflected more strongly in experiential and action-based processes than in abstract or metacognitive components of the scientific method.

3.4 Results for Research Question 3

The interview findings revealed recurring and systematic patterns of misunderstanding, indicating that students' knowledge was functional but not fully consolidated.

Students were generally able to express predictions. However, these were often not formulated as testable scientific hypotheses. In many cases, responses lacked clear causal relationships or were expressed as simple statements about what might happen, without justification that could be empirically tested. In other cases, students provided explanations based on intuitive reasoning, but these were not clearly structured as conditional or testable statements. These findings suggest that students tend to associate hypotheses only with prediction, rather than with a structured formulation that includes a cause-and-effect relationship and can be systematically tested.

Although many students demonstrated awareness of basic experimental procedures, difficulties were observed in controlling variables and designing systematic comparisons. Some students proposed experimental setups without ensuring that only one variable was changed, while others described incomplete procedures. In contrast, a smaller group of students provided more structured responses, describing parallel conditions while keeping other factors constant. This variation suggests uneven understanding of controlled experimentation.

A prominent misconception concerns the distinction between observation and measurement. Many students described observation as a process involving the use of instruments, such as thermometers, while others defined measurement in terms of sensory perception (e.g., touch). For instance, students stated that they would “observe with a thermometer” or “measure with the hand”. These responses indicate that students do not clearly differentiate between qualitative observation and quantitative measurement.

Significant difficulties were also identified in the process of drawing scientific conclusions. Only a portion of the students described conclusions as resulting from the comparison between initial hypotheses and collected data. Many responses focused instead on observing whether an outcome “worked” or on simply describing the results of an experiment without interpretation. Others referred to discussion with peers as a primary means of reaching conclusions. These patterns suggest that students do not fully conceptualize conclusion drawing as a process of evidence-based reasoning.

A recurring pattern in students’ responses involved references to processes related to constructing and testing the functionality of objects. In several cases, students described scientific investigation as a process of “building something and checking if it works” or evaluating whether a result is successful based on its functionality. These responses indicate that students tend to emphasize outcome-oriented practices, focusing on functionality rather than on systematic data analysis.

Overall, the findings indicate that students’ difficulties are not isolated but form coherent patterns. Students appear to have developed a basic, action-oriented understanding of scientific processes.

3.5 Relationships Between Variables (Correlation Analysis)

Statistically significant positive correlations were found among all examined variables. The analysis focused on the relationships between: (a) students’ self-reported knowledge of how scientists work (G1), (b) their belief in the validity of the scientific method (G4), and (c) the perceived contribution of scientific method processes to understanding scientific concepts (MEAN_G5) (Table 4).

The results revealed statistically significant positive correlations among all examined variables. Specifically, a moderate positive correlation was found between students’ knowledge of the scientific method (G1) and their belief in its validity (G4) ($\rho = 0.382$, $p < 0.001$), indicating that students who reported higher familiarity with how scientists work were more likely to express stronger confidence in the reliability of the scientific method.

In addition, a statistically significant weak to moderate positive correlation was identified between students' knowledge of the scientific method (G1) and the perceived contribution of its processes to understanding scientific concepts (MEAN_G5) ($\rho = 0.336$, $p < 0.001$). This finding suggests that students who demonstrated greater awareness of scientific practices tended to attribute higher learning value to engaging in these processes.

Finally, a statistically significant but weaker positive correlation was observed between students' belief in the validity of the scientific method (G4) and the perceived contribution of its processes (MEAN_G5) ($\rho = 0.260$, $p = 0.006$). This result indicates that although trust in the scientific method is associated with its perceived educational value, this relationship is less pronounced compared to the association involving students' knowledge of the method.

Table 4. Spearman Correlations Among G1, G4, and MEAN_G5

Variables	G1	G4	MEAN_G5
G1	$\rho = 1$	$\rho = 0.382$ $p < 0.001$	$\rho = 0.336$ $p < 0.001$
G4	$\rho = 0.382$ $p < 0.001$	$\rho = 1$	$\rho = 0.260$ $p = 0.006$
MEAN_G5	$\rho = 0.336$ $p < 0.001$	$\rho = 0.260$ $p = 0.006$	$\rho = 1$

Overall, the findings point to a coherent pattern in which knowledge of the scientific method appears to be more strongly associated with both epistemological beliefs and perceived learning benefits, whereas belief alone shows a weaker relationship with the perceived contribution of scientific processes.

These findings reveal meaningful relationships among knowledge, beliefs, and the perceived educational value of scientific method processes. In the following section, these results are interpreted within the framework of Cultural-Historical Activity Theory (CHAT), aiming to provide a deeper understanding of how students' engagement in scientific inquiry processes contributes to the development of both conceptual understanding and epistemological beliefs.

4. Discussion

The present study examined the development of primary school students' scientific method skills within a STEM-based instructional context, integrating quantitative and qualitative data to provide a comprehensive understanding of students' learning outcomes and underlying cognitive processes.

4.1 Development of Skills (RQ1)

The overall pattern of findings suggests that students developed a functional understanding of the scientific method, although the depth of this understanding varied across different cognitive demands. Rather than reflecting a uniform acquisition of scientific practices, students' performance indicates a progression from recognizing scientific processes toward their independent retrieval and application, with the latter remaining more challenging.

The discrepancy between recognition and independent recall of scientific method procedures suggests that different forms of assessment capture different levels of conceptual development. Recognition questions primarily assess the ability to identify scientific practices, while open-ended questions require students to retrieve, organize, and articulate these practices without external support. Consequently, lower performance in recall and application should not necessarily be interpreted as a lack of understanding, but rather as evidence that knowledge has not yet been fully internalized and is not easily transferable.

The greater difficulty observed in designing experiments and drawing conclusions based on evidence is consistent with the higher cognitive demands of these practices. Unlike observation or measurement, these processes require students to coordinate multiple sources of information, engage in abstract reasoning, and justify decisions using scientific evidence. Such abilities are usually developed gradually through repeated opportunities for inquiry and reflection.

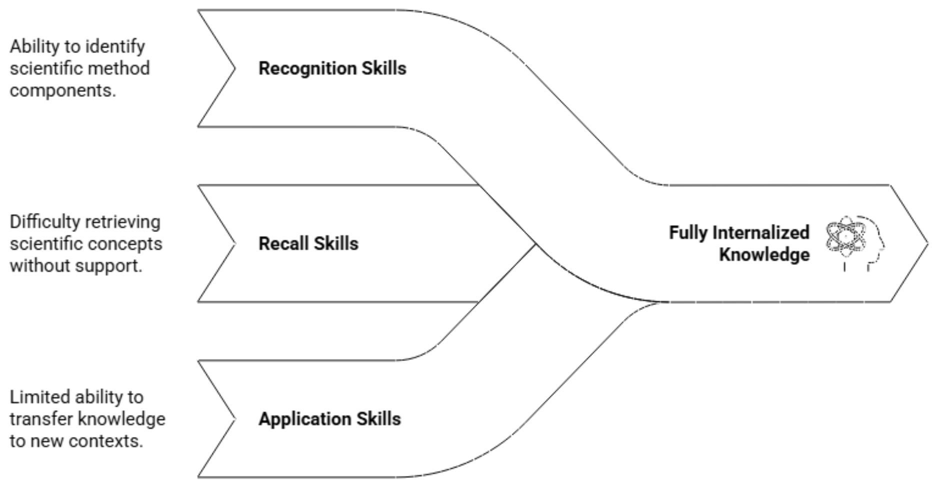

Figure 1. Pathway of Internalization of Scientific Processes

Within the context of the CHAT, the recognition of procedures (from options given in the questionnaire) reflects an initial stage of externalization, where it shows the successful interaction of students with externally available tools such as worksheets with guided activities and with the other subjects of the activity (classmates and teacher). The recall of procedures (in interviews without ready-made options), and their application in new situations is an indication of the internalization of scientific practices as cognitive tools. Therefore, the difficulties recorded at the level of recall and application can be interpreted as indications that internalization has not been fully completed. They also constitute secondary contradictions within the system of the activity, which limit the ability of students to transform their knowledge into functional tools of thought and action (**Figure 1**).

4.2 Students' Evaluation of Scientific Processes in Learning Concepts (RQ2)

Student evaluations suggest that the perceived educational value of scientific procedures depends not only on their role in scientific inquiry, but also on how directly students experience them during learning activities. Procedures that involve direct manipulation of materials, observation of phenomena, and immediate feedback appear to be more readily recognized as contributing to conceptual understanding than procedures that require abstract reasoning.

This difference may reflect the developmental characteristics of primary school learners. Whereas observation and experimentation produce visible and immediate outcomes, hypothesis formulation and evidence-based reasoning require students to coordinate prior knowledge, prediction, reflection, and justification. Consequently, these processes may be perceived as less directly connected to learning, despite being fundamental components of scientific inquiry.

From a CHAT perspective, this pattern suggests that students initially attribute greater learning value to those scientific practices that are mediated through direct interaction with tools, materials, and collaborative activity. These externally mediated actions form the foundation upon which more abstract forms of scientific reasoning are gradually internalized. Therefore, the comparatively lower rating of hypothesis formulation and inference should not be interpreted as a weakness of the intervention itself, but rather as evidence that higher-order epistemological practices require longer periods of participation, reflection, and guided support before students can fully recognize their contribution to conceptual understanding.

4.3 Interpretation of Misconceptions (RQ3)

The qualitative interview data indicate that students' difficulties do not represent isolated misconceptions but reflect three broader patterns in the development of scientific thinking. These patterns concern scientific reasoning and conceptual differentiation.

The first pattern relates to scientific reasoning. The interview responses suggest that students experienced greater difficulty when scientific processes required the coordination of multiple forms of reasoning, such as linking hypotheses with evidence, controlling variables, or justifying conclusions. These difficulties suggest that students had not yet fully appropriated the epistemic logic that connects the individual processes of scientific inquiry into a coherent reasoning framework.

A second pattern concerns conceptual differentiation. The confusion between observation and measurement indicates that students often understood scientific processes as practical actions without clearly distinguishing their different purposes. The interview data therefore suggest that students were generally able to describe what they did during the activities, but were less able to explain why each scientific process served a distinct role within the investigation.

The two patterns can be seen as evidence that students are still in the process of internalizing the processes of the scientific method. The difficulties identified in the interviews therefore represent developmental stages in this transition, revealing aspects of scientific thinking that require further mediation and not just conceptual correction.

4.4 Conclusion

This study examined the development of elementary school students' scientific method skills through a STEM-based instructional intervention using a convergent mixed-methods approach. Findings indicate that students developed a working understanding of basic scientific processes, particularly those directly related to hands-on activity, such as observation, experimentation, and measurement. However, results also indicate that this understanding was not fully established, as students had more difficulty recalling, explaining, and independently applying processes that require higher-level reasoning rather than direct hands-on engagement, such as formulating hypotheses, designing experiments, and drawing conclusions based on evidence.

The study also highlights the value of incorporating quantitative and qualitative data when examining students' scientific thinking. While questionnaire data indicated that students were able to identify various scientific method processes, interview data revealed more complex patterns of reasoning, including misconceptions, and difficulties in applying them. These findings suggest that students' development of scientific method skills should not be understood as the simple acquisition of individual processes, but as a gradual process of internalization.

From a CHAT perspective, the STEM intervention provided a learning-mediated environment in which material tools, collaborative activity, and scientific method processes supported students' engagement with scientific inquiry. At the same time, the difficulties identified in students' responses can be interpreted as productive tensions within the activity system, indicating areas where further instructional mediation is needed.

Overall, the study suggests that STEM education can support the development of scientific method skills in primary education, especially when students are actively engaged in inquiry-based and experiential learning activities. Future educational plans should place greater emphasis on supporting students to move beyond recognition to independent application, reflection, and evidence-based reasoning.

4.5 Interpreting the Correlations through CHAT

The observed associations suggest that students' knowledge of the scientific method, their confidence in its validity, and their perceptions of the contribution of scientific processes to learning are interrelated dimensions rather than independent characteristics. This overall pattern suggests that a more developed understanding of the scientific method is accompanied by more positive beliefs about both its reliability and its educational value.

From the perspective of Cultural-Historical Activity Theory (CHAT), this pattern is consistent with the view that the scientific method functions as a mediating cultural tool within learning activity. Through participation in inquiry-based activities, students gradually acquire not only scientific processes but also the ways of thinking and reasoning that these processes represent. As scientific practices become increasingly meaningful in the system of activities, students appear to develop greater confidence in the scientific method, while recognizing its contribution to conceptual understanding.

However, these interpretations should not be considered causal. The findings are based on correlational analyses that do not demonstrate causal relationships between the variables examined.

4.6 Limitations

This study should be interpreted with some limitations in mind, as they may affect how the findings are understood and generalized. The use of convenience sampling limits the ability to generalize the results. In addition, the relatively short duration of the intervention may reflect an early stage of skill development rather than a fully developed understanding. The study did not examine the long-term retention of these skills, which limits conclusions about the overall effectiveness of the intervention. Finally, the absence of a control group limits the ability to attribute the observed changes solely to the STEM intervention, thereby limiting the strength of causal inferences.

It should also be noted that this study is part of a broader research effort that aims to combine scientific method processes and engineering design within a single STEM program. The presence of both approaches may have led to some confusion among students in distinguishing between different processes. However, this issue was not examined further in the present study, as it was beyond its focus.

4.7 Implications

The findings of this study have important implications for the design and implementation of STEM teaching in primary education.

First, there is a need to support the teaching of scientific processes beyond simple recognition, with greater emphasis on helping students recall, express, and apply them independently in open-ended situations. The difference found between recognition and independent use suggests that teaching should include activities that promote knowledge transfer and independent thinking.

In addition, the results show that students respond more positively and effectively to hands-on activities, such as observation and experimentation. Therefore, experiential and inquiry-based approaches are important for developing scientific thinking. However, processes related to thinking, such as forming hypotheses and drawing conclusions, also need to be supported more systematically, as they appear to be less developed. The findings point to the importance of balancing practical engagement with reflection. While experimental activities increase student participation, they should be combined with guided opportunities to interpret and connect data, so that students can develop a more complete understanding of scientific processes.

Finally, the difficulties students showed in distinguishing between process of observation and measurement highlight the need for clear and explicit teaching of these concepts.

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Authors contributions

Georgios Koukoulis conceived and designed the study, collected and analyzed the data, interpreted the findings, and drafted the manuscript. Professor Katerini Plakitsi contributed to the study design, supervised the research, critically revised the manuscript, and provided scientific guidance throughout the study. Both authors read and approved the final manuscript.

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