Exploring the Development of Questioning Inquiry Skill in Secondary School Students via Physics Inquiry-Based Learning Experiments

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Abstract

Science process skills encompass cognitive abilities for evidence-based inquiry, integral to inquiry-based learning, promoting holistic development and academic success. The current study aims to assess Grade 10 & 11 school students in the "Identify Testable Questions" inquiry process skills based on the Science Inquiry Skills Framework after participating in inquiry-based learning activities. Three inquiry-based learning series (confirmatory, structured, and guided) were developed, focusing on "Newtonian Mechanics," with small groups of 3-4 students on a total N=22. Students' responses were categorized into four levels based on their epistemological accuracy. The study's findings indicate that students' performance steadily improves in each inquiry type, which is evident in rising the average values. Significant variations were uncovered through paired samples t-tests, with Structured inquiry yielding higher mean scores than Confirmative inquiry and Guided inquiry outperforming Structured inquiry. Hake Gain indices demonstrated a medium gain (g=.39) between initial and final assessments for Guided inquiry. The assessment results underscored the diverse effectiveness of each inquiry type, emphasizing the time and engagement required for notable skill improvement. Open-ended question analysis revealed five distinct response patterns, showcasing a positive transformation in students' explanations aligned with established scientific knowledge. The study highlights the pedagogical value of guiding students through progressively advanced inquiry types, contributing valuable insights to the discourse on effective inquiry-based learning practices and their impact on scientific skill development.

Keywords: *Science Process Skills, Inquiry-Based Learning, Student Performance*

1. Introduction

Exploring the natural world, forming evidence-based explanations, and engaging students in activities that enhance their understanding of scientific concepts and methodologies are all part of the inquiry process, as defined by the National Science Education Standards [1]. Inquiry-based learning is how students acquire science process skills, essential cognitive and procedural abilities utilized for scientific inquiry and problem-solving in science education [2]. According to Turiman et al. [3], science process skills can be classified into two categories: Basic and Integrated skills. Basic skills are fundamental and serve as a foundation for Integrated skills. These skills involve observing, classifying, measuring, numerical analysis, making inferences and predictions, effective communication, and understanding spatial and temporal relationships. Integrated skills, on the other hand, include Making Inquiry Questions, Formulating Hypotheses, Controlling Variables, Making Operational Definitions, and Interpreting Data. Research has shown that Inquiry-Based Learning (IBL) consistently improves students' inquiry skills. Studies such as Adnyana & Citrawathi [4] and Dewi, Mayasari & Handhika [5] support this. Moreover, the effectiveness of IBL in the development of skills depends on the level of inquiry. Guided inquiry, in particular, has yielded better outcomes, as noted by Brata & Suriani [6].

When conducting scientific inquiry, an initial investigable question about the physical world is typically asked, and a formally stated hypothesis is sometimes stated [7]. Investigable questions are open-ended questions that serve as guiding prompts in research processes. They help students build knowledge, develop critical thinking skills, and engage in active learning. By investigable questions, we mean questions students can answer with the materials provided. To answer such questions, students must understand the difference between dependent, independent, and control variables. They should also understand the possible cause-and-effect relationship between the dependent and independent variables [8].

When students create a research question, they should identify the variables that may affect the phenomenon they want to study. They need to consider which variables might influence the dependent variable. While it is difficult to specify all independent variables for every phenomenon, it is easier for students to identify independent variables related to the materials' properties. However, when independent variables involve environmental conditions, it can be challenging for students to recognize them [8]. Therefore, providing illustrations of available materials in the form of sketches for each investigation can be helpful to facilitate students' understanding. As students engage in the investigation process, they must ensure that the questions they ask are investigable. Such questions must be answered through active experimentation and not just by responding to causal-type questions like *"Why does something happen."* For instance, questions like *"Why does an object undergo accelerated motion in free fall?"* can be answered simply through a literature search or Newton's Second Law study. To ensure that the investigation is meaningful, students should choose propositions that require research through active experimentation for answers. Moreover, the questions (or hypotheses) should guide students toward classifications, such as "how does it depend on..." or "what is the relationship between..." [8].

As mentioned above, students can also develop researchable hypotheses and investigable questions. These hypotheses should guide them toward classifications. The difference between investigable questions and hypotheses lies in how they are formulated and their role in designing research. Scientific hypotheses can be categorized into three types: generalized statements about a phenomenon that can lead to a Law, explanatory hypotheses about how a phenomenon functions that may lead to a scientific Theory, and prediction hypotheses that make predictions [9]. For example, a Law hypothesis could be: *"The time of free fall of an object is proportional to its release height."* If this hypothesis is correct, it leads us to a descriptive Law where time is proportional to height. However, these hypotheses are not directly associated with leading students to active experimentation and subsequently to classification. A Theory hypothesis could be: *"The free fall time of an object is affected by its mass."* To confirm or reject this hypothesis, letting two objects with different masses undergo free fall is sufficient. If differences in their fall times are detected, the hypothesis is correct, leading to a Theory. A prediction hypothesis could be: *"The mass of an object affects its free fall time."* Again, to confirm or reject this hypothesis, letting two objects with different masses undergo free falls is sufficient. Based on the above arguments, it may be concluded that investigable questions like "how does A depends on B..." or "what is the relationship between A and B..." direct students more intently towards active experimentation and classification. Therefore, a "template" formulation of an investigable question regarding the dependence of the dependent variable on the independent one may take the form: *"In what way does the (independent) variable affect the (dependent) variable?"* or *"What is the relationship between the (independent) variable and the (dependent) variable?"*.

When teachers connect the theoretical foundation with the practical application of inquiry-based learning, it becomes apparent that carefully formulating investigable questions is crucial for students actively experimenting and classifying. Therefore, this study aimed to investigate the development of students' questioning skills in secondary school by implementing Physics Inquiry-Based Learning Experiments. This led to the formulation of the following research questions:

a. How does students' understanding regarding the "*Identify testable questions*" inquiry skill develop when working in inquiry-based learning?

b. What patterns of student understanding emerge based on their responses?

c. How do gender and grade affect the development of the "*Identify testable questions*" inquiry skill?

2. Materials and methods

2.1 Sample

The sample for this study is N=22 students, 17 of which were studying in Grade-10, while the rest in Grade-11. All students were between 15 and 16 years of age, 17 were boys and 5 girls. All students attended public schools in the Larissa region (Greece) while, at the same time, they were enrolled in a private secondary education Tutorial Center, in the same area. Their performance levels in Physics varied with grades spanning from 10 to 20 out of 20, with an average performance score of 15/20. The sample was considered non-probabilistic due to the researcher's convenient access as an educator at the specific tutorial center during the study period. The students' socio-economic background was categorized as medium to high.

2.2 Student's activities

The sample of N=22 students was randomly divided into four groups, of 5-6 students each. The Inquiry Framework proposed by Pedaste et.al. [10] has been adopted for this work. In this framework, a structured approach to inquiry-based learning in science education, is proposed, comprising four distinct phases. The "Orientation" phase introduces the topic, capturing students' interest, while the "Conceptualization" phase involves developing a foundational understanding and formulating questions. The "Investigation" phase is central to the process, as students actively engage in experiments and data collection. Finally, the “Conclusion” phase focuses on drawing conclusions, reflecting on the learning experience, and communicating findings. Emphasizing the iterative nature of inquiry, the framework guides students and teachers through a comprehensive exploration of scientific concepts, fostering a deeper understanding of the subject matter. Three Inquiry-based learning series (confirmatory, structured, and guided) were developed, focusing on "Newtonian Mechanics". The provided scaffolding was consistent with the principles of inquiry-based learning [11]. In the confirmatory inquiry, increased support was provided during the “Questioning” and “Experimentation” phases, while less assistance was given in the “Conclusion” phase. During the “Questioning” phase, the teacher guided students through methodological issues, such as stating the aim of the research, identifying dependent and independent variables, while students were practicing the scheme "How does variable x affect variable x?". In the subsequent investigations, based on structured or guided inquiry, students followed the same steps with less and less scaffolding through guiding questions and verbal assistance. At the end of each investigation, students wrote an experimental report, sharing results with other groups, prompting reflection on their processes.

2.3 Materials

The total Inquiry-based teaching-learning sequence lasted about 4 months, from February to May 2023. It consists of 18 sessions, of a duration of 40-45 minutes each. During their investigations, students used hands-on laboratory equipment and simulations. The topics for the Inquiry-based series were “Acceleration”, “Fall”, “Projectile motion” and “Collisions”. In exploring acceleration, students measured variables impacting a cart's acceleration using wireless Pasco smart carts, adjustable inclined planes, mass sets, pulleys, a fan, and various surfaces. “Fall” experiments involved determining the impact of variables on the time it takes for a spherical object to descend, utilizing an electromagnet release system, a timer, and distance-measuring tools. For “Projectile motion” investigations, students utilized a Phet simulation (https://phet.colorado.edu) to explore how variables like gravity, mass, initial velocity, launch height, and angle affect a projectile’s range. “Collisions” were studied by examining the percentage change in kinetic energy in elastic collisions using wireless Pasco Carts, magnets, and masses. Controlled experiments were conducted for each investigation, ensuring systematic exploration of specific questions while maintaining constant variables.

2.4 Development of the assessment

The development and validation of the assessment employed in this research required an extensive examination of literature concerning inquiry-based learning and evaluating inquiry skills within secondary school education. An extensive literature survey was conducted on Google Scholar (https://scholar.google.gr) and focused on studies which concentrate on secondary school education, and particularly those addressing the teaching of Physical Sciences through inquiry or discovery-based methods. The survey spanned from 1980 to 2022, and findings were limited to English or Greek. This comprehensive approach led to the examination of various science inquiry assessment records [12, 13, 14], where the content and question style of the tests were scrutinized. Additionally, the study explored several curricula, such as the NRC K-12 science and engineering curriculum, which outlines the eight fundamental inquiry skills known as practices [1]. It is worth stating that in the literature, no skill regarding developing testable questions exists [15]. After the literature review, the PTI Science Inquiry Skills Framework by Lou et al. [16] was adopted, whereas the operational definition for *“Identify testable questions”* is as follows; *“Given a description of research interest and investigation set up, identify the testable question.”*

Four assessments were developed to evaluate the several Inquiry Process Skills. Initially, the content of each assessment was curated to feature questions situated within the realm of Physics, specifically Newtonian mechanics, aligning with literature recommendations for facilitating comparative analysis of students' learning gains [17]. A standardized structure for each assessment was chosen, employing multiple-choice responses. Additionally, each questionnaire item was accompanied by an open-ended prompt for a brief justification, to enhance the reliability of the scoring. Each question consisted of four options, one of which was the correct answer. After each question, the students were asked to justify their choice by answering an open-ended question. The first question in each assessment aimed at assessing the students' understanding of the *“Identify Test Questions”* inquiry skill, developed when working in Inquiry-based learning. Each assessment started with a brief scenario: “*You want to investigate the factors which affect how far a toy car can travel on a horizontal surface. To do this, you have at your disposal the following materials (tape measure, a toy car, glass marbles a stopwatch, a digital scale, a ramp that you can lean on three boxes and, various flat surfaces on which to place the ramp). According to the materials you have, which of the following* *questions is appropriate for you to perform an experimental inquiry?”* After that, each student could select one of four choices, as presented in Table 1.

Table 1. The structure of each question regarding the “Identify testable questions” inquiry skill.

Choice	Description
A	An option that expressed a causative-type question (e.g., why does an object undergo uniform accelerated motion when a constant force is applied to it?), which could be answered by collecting information through a literature search or studying Newton's Second Law Theory.
B	An option that expresses a question that does not require investigation and can be answered with a single measurement (e.g., how long does it take for the ball to reach the ground if we drop it from a height of 2 m?).
C	An option that referred to a general question that was not directly investigable but could be the purpose of an investigation.
D	The correct option: A question that was investigable and could be answered through active experimentation using the provided materials.

Note: The possible choices were shuffled randomly by software.

2.5 Scoring of the responses

The participants' responses to the open-ended prompts, were categorized into four levels based on their scientific accuracy, as shown in Table 2. Each level was scored with 0, 1, 2, or 3. At the lowest level (Level E0), students’ responses were classified as either non-existent or incorrect. At the highest level (Level E3), students’ responses were those in which the correct option was selected and fully justified.

Table 2. Rubric for the assessment of the selected inquiry process skills.

Ranking of the answer	Description	Score
Level 0	Student does not answer anything or answers incorrectly	0
Level 1	Student chooses the correct option but does not justify it or justifies it incorrectly	1
Level 2	Student chooses the correct option but justifies it inadequately	2
Level 3	Student chooses the correct option and justifies it fully	3

2.6 Data analysis

In this study a paired-samples t-test was used to explore potential associations among students' skills, aiming to assess whether there are statistically significant differences in mean skill scores within each inquiry type. The significance level (p-value) for all analyses was set at $p=.05$. IBM SPSS 26.0 software was employed for data analysis. Additionally, the study employed the normalized Hake Gain index, following Marx & Cummings's [18] recommendation, to gauge the change in students' inquiry skills before and after interventions based on the initial and final granted IPST. The Hake Gain indexes, as defined by Hake [19], categorize gains as marginal ($0 < G_{ave} \leq 0.3$), proficient ($0.3 < G_{ave} < 0.5$), and exemplary ($G_{ave} \geq 0.5$).

3. Results

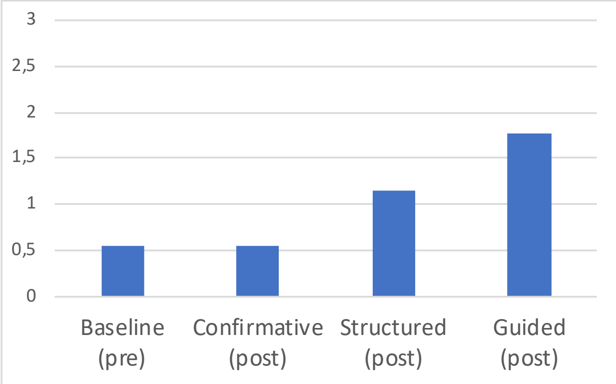
3.1 Average performance scores of students on each question of each IPST

Table 3 and Figure 1 present the progression of mean values for the *“Identify Testable Questions”* skill (from now on referred to as Questioning, QU) after administering each Inquiry Process Skills Test (IPST). Baseline, refers to the initial administration of the ISPT, prior to the Inquiry-based series. The data indicates a consistent upward trend in student performance, with the average values showing a continual increase from one test to the subsequent one.

Table 3. The mean values for Questioning after implementing each type of Inquiry.

Independent Variable	Mean (SD)
Baseline (IPST1)	.55 (.51)
Confirmative (IPST2)	.55 (.74)
Structured (IPST3)	1.14 (.94)
Guided (IPST4)	1.77 (.97)

Figure 1: The progression of mean values for Questioning.



Implementing paired samples t-test, statistical differences were observed regarding the mean values between different types of inquiries. Specifically, students after attending the Structured inquiry had greater mean scores (M=1.14, SD=.94) in "Questioning" than students attending the Confirmative inquiry (M=.55, SD=.74), t(2.890,21), p=.009 with a 95% confidence interval from .17 to 1.02. Also students attending the Guided inquiry had greater mean score (M=1.77, SD=.97) in "Questioning" than students attending the Structured inquiry (M=1.14, SD=.94) t(3.309,21), p=.003 with a 95% confidence interval from .24 to 1.04.

Calculating the Hake Gain indices between the initial (Baseline-pre) and final IPST (Guided-post), a proficient (medium) gain with value G_{ave}=.39 was found. Finally, implementing paired samples t-test for the two skills between the baseline (pre) measurement and after the Guided (post) type of inquiry, students' mean scores were greater at the end of the whole intervention with mean scores (M=.55, SD=.51) in the Baseline (pre) measurement, versus (M=1.77, SD=.97) for the Guided (post) measurement, t(6.827,21), p<.001 with a 95% confidence interval from .70 to 1.76. The assessment results suggest varying effectiveness of each inquiry type, with "Identifying testable questions" requiring considerable time and student engagement for significant enhancement.

Five different patterns emerged by studying students' responses to the open-ended questions (Table 4) and their frequency appearance was noted (Table 5). Through the analysis of various patterns in student responses, it was discovered that as students become engaged in more advanced types of inquiry (Confirmative, Structured, Guided), their responses become more scientifically accurate and shift from mere attempts to explain a phenomenon's behavior to justifications that closely align with scientific knowledge. This shift is due to their choice of investigations that involve taking multiple measurements or the use of appropriate question formats that consist of a dependent and an independent variable.

Table 4. Patterns on students' answers regarding "Identify Testable Questions".

Pattern	Student Answer
#1	Student does not answer, or raises the question without giving an answer.
#2	Student assumes that there is some general purpose of inquiry, or tries to explain why a specific phenomenon happens.
#3	Student states the materials he will use, or states how he will do the investigation, or states that he/she will change a variable and measure something else.
#4	States that the selected question can provide him/her measurements or leads to research.
#5	States that the question is testable because it has a dependent and independent variable relationship.

Table 5. Students' counts on each pattern on their answers regarding "Identify Testable Questions".

Pattern	Baseline (pre) Counts (%)	Confirmative (post) Counts (%)	Structured (post) Counts (%)	Guided (post) Counts (%)
#1	7 (31,8)	5 (22,7)	7 (31,8)	2 (9,1)
#2	12 (54,5)	8 (36,4)	1 (4,5)	1 (4,5)
#3	3 (13,6)	8 (36,4)	9 (40,9)	4 (18,2)
#4	0 (0)	0 (0)	2 (9,1)	10 (45,5)
#5	0 (0)	1 (4,5)	3 (13,6)	5 (22,7)

Regarding gender, no statistical differences were observed. In contrast, statistical differences were found regarding students' grade in the structured inquiry, where 11th-grade students (M=2.20, SD=.84) had a higher mean score than 10th-graders (M=0.82, SD=0.73), t(3.604,20), p=.002 with a 95% confidence interval from .58 to 2.17.

4. Conclusion

The study presented a thorough exploration into students' understanding and skill development in the "Identify testable questions" inquiry skill within inquiry-based learning, focusing on three distinct inquiry types: confirmative, structured, and guided, all centered around Newtonian Mechanics. Meticulous assessment, aided by tailored scaffolding and hands-on exploration, shed light on the complex factors influencing students' learning experiences. The adoption of a standardized multiple-choice structure and a scoring rubric contributed to the reliability and depth of the assessment of the targeted skill.

The research unfolded with a methodical analysis of students' responses and performance, revealing patterns and insights that underscored the profound impact of inquiry-based learning on nurturing the selected scientific inquiry skill. Applying paired samples t-tests brought forth significant statistical variances in mean values among the different inquiry types. Notably, students in the Structured inquiry exhibited higher mean scores than those in the Confirmative inquiry, and those in the Guided inquiry demonstrated a higher mean score than those in the Structured inquiry.

The evaluation extended to Hake Gain indices, unveiling a proficient (medium) gain with a value of G_{ave}=.39 between the initial (Baseline-pre) and final IPST (Guided-post). In summary, the assessment results highlighted varying effectiveness across each inquiry type, emphasizing the substantial time and student engagement required for significant improvement in the skill of "Identifying testable questions."

Furthermore, analyzing students' responses to open-ended questions revealed five distinct patterns, providing valuable insights. The identified trend showcased a positive transformation in students' explanations from basic attempts to elucidate a phenomenon's behavior to justifications closely aligned with established scientific knowledge as they progressed through different inquiry types.

The authors attribute these positive changes in response quality to the students' engagement in investigations involving multiple measurements or question formats with a clear distinction between dependent and independent variables. This highlights the pedagogical value of guiding students through progressively advanced inquiry types, fostering a more sophisticated and scientifically grounded approach to problem-solving and explanation. The study contributes valuable insights to the ongoing debate on effective inquiry-based learning practices and their impact on the development in scientific inquiry skills.

5. Ethical considerations

All students in the research were participated willingly. They participated anonymously, and their privacy was safeguarded through individual six-digit codes, known only to them. Taking account students' age, their parents were informed on the scope of the research and the way it will be carried out. Their parents have signed a relevant consent form. This whole process has been approved by the Ethics Committee of the Aristotle University of Thessaloniki (AUTH) (No 98642/2023).

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