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METHODOLOGY FOR DEVELOPING STUDENTS' DESIGN COMPETENCE THROUGH GENERAL PHYSICS LABORATORY ACTIVITIES

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Abstract

Following a laboratory instruction does not, in itself, demonstrate the ability to design an experiment. This article presents a methodology for developing students' design competence in general physics laboratory activities. The study systematises the theoretical and methodological materials of the dissertation through conceptual analysis, functional comparison and pedagogical modelling. A structural–functional model connects goal-setting, content, process and diagnostic–outcome components. Scientific inquiry methods are coordinated with problem-based learning, project work, practical tasks and reflection. The instructional process comprises five stages: motivational–problem, theoretical–analytical, design–planning, experimental–practical and analytical–reflective. A laboratory design map makes the relationship among the problem, hypothesis, equipment, measurement procedure and interpretation explicit. The methodology is illustrated through the design of a pendulum investigation and differentiated open tasks in mechanics, molecular physics, electricity, optics and oscillations. Virtual modelling and real experimentation are connected through comparison and revision. Assessment distinguishes six criteria and four qualitative levels of performance, with attention to both the process and the product of the investigation. The principal result is a methodological system linking physical explanation, experimental decisions, documented evidence and reflective improvement. The article does not report a new pedagogical experiment or a measured effectiveness estimate.

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Keywords: Design competence; general physics; laboratory activities; experimental design; scientific inquiry; project-based learning; virtual laboratory; reflective assessment.

Introduction

The educational value of a physics laboratory is not exhausted by obtaining a numerical result. A student needs to understand what is being measured, justify the selected method, recognise the conditions under which a physical model is applicable and explain differences between expectation and observation. When the sequence of actions is completely prescribed, a finished report may show that the instructions were followed without revealing whether the student could design the investigation independently.

The problem addressed in this study is the separation of physical knowledge, practical operations and the decisions that connect them. Design competence is considered through the student's ability to formulate an experimental problem, plan an investigation, choose and use resources, interpret evidence and propose an improvement. The purpose of this article is to explain the relationships among the methodological model, the five-stage laboratory sequence, open project tasks and assessment. The emphasis is on justified experimental decisions rather than on the production of a device or report alone.

Literature Review

K.T. Suyarov examines the development of research skills through physics experiments [1]. J.E. Usarov addresses the relationship between key and subject-specific competencies in physics education [2]. These contributions support the organisation of laboratory work as a setting for purposeful learning activity rather than only for demonstrating a known result. In the Russian didactic tradition, A.V. Usova analyses the formation of scientific concepts [3], while V.G. Razumovsky considers the development of creative abilities in physics learning [4]. Their perspectives connect conceptual understanding with the student's own cognitive and practical actions.

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Etkina and colleagues present scientific process abilities, formative tasks and assessment rubrics for introductory physics [5]. Their work is relevant to the need to make experimental reasoning visible through observable actions. Hofstein and Lunetta discuss the laboratory as an environment for inquiry, interpretation and learning [6]. Perkins and colleagues describe interactive simulations for physics teaching and learning [7]. In the proposed methodology, simulations are used in relation to experimental planning and comparison, not as an assumption that virtual activity reproduces every feature of a physical apparatus.

Kolb's account of experiential learning provides a foundation for connecting practical experience with reflection and subsequent action [8]. These theoretical positions have complementary roles: scientific concepts guide the choice of a model, inquiry generates and tests a prediction, project activity organises decisions into a feasible procedure, and reflection supports revision. The methodological task is to coordinate these functions within the available laboratory content, equipment and teaching conditions.

Methodology and Research Design

The article is based on the systematisation of the theoretical foundations and methodological developments presented in the first two chapters of the dissertation. Conceptual analysis clarified the meaning of design competence in laboratory work. Functional comparison distinguished scientific inquiry methods from the methods used to organise students' learning. Pedagogical modelling connected the structural components, instructional stages, task products and diagnostic evidence. The pendulum investigation and the unit-specific tasks are methodological illustrations drawn from this task system, not reports of newly collected measurements.

The assessment discussion follows the detailed six-criterion, four-level account in Section 2.3. The earlier three-level model diagram is not used as a scoring scale, and no numerical equivalence with an externally validated rubric is asserted. The article does not report participant-level data, comparison-group results or statistical evidence of effectiveness. Its results concern the

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organisation of a methodological system; the reliability of the diagnostic arrangements and the magnitude of educational effects require separate investigation.

Research Results

Result 1. A Structural–Functional Model of Laboratory Design Competence

Design competence is understood as the integration of physical knowledge, experimental planning, practical action, analysis and reflection in solving a laboratory problem. This interpretation makes the student's decisions part of the learning outcome. The structural–functional model contains four connected components (Table 1). Their relationship is iterative: an observed difficulty may require revision of the procedure, a reconsideration of the model or additional conceptual support.

Table 1. Components of the methodological model

Component	Function in laboratory learning
Goal-setting	Define the intended capacity to identify a problem, design an investigation and justify experimental decisions.
Content	Connect physical concepts, scientific inquiry methods, didactic principles and the conditions required for laboratory work.
Process–activity	Organise individual and collaborative planning, modelling, experimentation, analysis, project defence and reflection.
Diagnostic–outcome	Examine documented actions and products, identify the level of independence and use feedback to improve subsequent work.

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Scientific inquiry methods and instructional methods have different but related functions. Observation, measurement, experimentation, modelling, comparison, analysis and synthesis provide ways of investigating a physical problem. Problem-based learning, project work, practical assignments and reflective discussion organise the student's participation in that investigation. The first group concerns how evidence and explanations are developed; the second concerns how these processes become accessible learning activities.

A laboratory project can result in an improved apparatus, an experimental arrangement, a measurement procedure, a computer model or an analytical report. The product is educationally meaningful when the student explains its physical basis and the decisions that shaped it. A working arrangement alone does not establish competence if the learner cannot explain why the equipment was selected, what variables were controlled or how the result should be interpreted.

Result 2. A Five-Stage Methodological Sequence

The proposed sequence consists of motivational–problem, theoretical–analytical, design–planning, experimental–practical and analytical–reflective stages. The eight more detailed project actions described in the methodology fit within these stages: identifying a problem, setting an objective, selecting the physical basis, designing the arrangement, conducting the experiment, processing results, defending the product and reflecting on the work. The stages organise learning; the detailed actions make the activity operational.

Stage 1 – motivational and problem-oriented. The teacher introduces a physical question or a technical difficulty that requires investigation. Students explain what is known, what remains uncertain and why the problem is worth solving. The objective is not to conceal essential safety information or prevent all support, but to retain a meaningful decision for the students. A task becomes project-oriented when the method or arrangement must be selected and justified rather than copied in full.

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Stage 2 – theoretical and analytical. Students identify the relevant physical concepts and relationships, examine the variables and formulate a testable expectation. They distinguish the idealised model from the conditions of the intended experiment. The teacher's questions direct attention to the connection between the proposed explanation and the quantities that can actually be measured. The output of this stage is a reasoned hypothesis and a physical basis for the investigation.

Stage 3 – design and planning. Students prepare a laboratory design map containing the problem, objective, hypothesis, equipment, diagram, measurement procedure, calculation plan, analysis and intended form of conclusion. Equipment selection is related to the quantity to be measured and the required measurement range. Students identify which conditions will be changed and which will be kept comparable. They prepare recording tables and discuss safety before assembling the apparatus. The map makes the proposed route from question to evidence explicit.

Stage 4 – experimental and practical. Students assemble the arrangement, carry out the planned measurements and record observations in a form that can be examined later. The teacher monitors safety and provides guiding support where a difficulty prevents progress. Changes to the procedure are recorded and explained. Data processing is connected to the experimental objective: a table or graph is prepared because it helps examine the proposed relationship, not simply because the report requires one.

Stage 5 – analytical and reflective. Students compare the evidence with the initial expectation, consider measurement limitations and defend their interpretation. Reflection addresses where the plan worked, where it required revision and how the investigation could be improved. A disagreement with the expected result is treated as a reason to examine the model, procedure and measurements rather than to hide the discrepancy. The final product includes a conclusion and a justified proposal for further work.

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The relationship among stages is more important than a rigidly repeated lesson script. The hypothesis influences the measurement plan, the plan determines the evidence available, and the evidence limits the conclusion that can be defended. A practical failure can therefore lead back to planning, while an unresolved discrepancy can lead back to the theoretical explanation. Such returns are part of the design process rather than signs that the learning sequence has been abandoned.

Result 3. Unit-Specific Tasks and a Pendulum Design Example

The common sequence is adapted to the physical content of each unit. Mechanics foregrounds the selection and control of variables; density investigations require a justified choice of measurement method; electrical work involves circuit design; and optics involves the relationship between a representation and the arrangement producing an image. Table 2 summarises the open tasks developed in the methodology.

Table 2. Open laboratory design tasks across general physics units

Physics unit	Design task	Main learning product
Mechanics	Plan a pendulum investigation to determine gravitational acceleration and examine ways to reduce measurement uncertainty.	Investigation plan, measurement record and justification of the procedure.
Molecular physics	Choose methods for determining the density of liquids or solids and compare their measurement limitations.	Method comparison, calculations and a reasoned choice.
Electricity and magnetism	Design a measurement arrangement to examine current–voltage relationships for different circuit elements.	Circuit diagram, measurement table and characteristic graph.
Geometrical optics	Develop a lens arrangement that produces a clear image of a specified size.	Optical diagram, experimental arrangement and explanation.
Oscillations and waves	Design an investigation of a spring oscillator's period in relation to mass and stiffness.	Variable-control plan, graph and evidence-based interpretation.

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The pendulum task illustrates how a familiar experiment can be reorganised around student decisions. The initial activity is observation: students examine the oscillation, distinguish the equilibrium position from motion and identify features that may complicate measurement. They then formulate the objective of determining gravitational acceleration and explain the physical model on which their proposed method depends. The example is an instructional sequence; no measurement values are supplied as research results.

Planning focuses on the choices that a conventional instruction sheet often makes in advance. Students decide how to measure length, how to organise timing, how many observations to repeat and how to record the results. They consider the starting conditions and the limitations of the available instruments. The design map requires an explanation of these decisions, making it possible for the teacher to identify a weakness before the experiment begins. Different groups may propose different procedures and compare their practical advantages.

Virtual modelling, where an appropriate resource is available, is used to examine the proposed relationship and rehearse the logic of the investigation. Students then carry out the real experiment and compare their observations with the model. The two activities are not interchangeable. The simulation makes a selected model available for manipulation, while the physical arrangement introduces measurement procedures and practical conditions that must be considered in the interpretation.

The final discussion returns to the quality of the design. Students explain whether the recorded evidence is sufficient for the intended conclusion, identify sources of discrepancy and propose changes to the arrangement or measurement sequence. Their defence includes the plan, observations, processed results and a reflection on the decisions taken. An improvement proposal must respond to an identified limitation; simply replacing an instrument with a more modern one does not explain why the investigation would become more informative.

The same logic supports the “predict–experiment–explain” and small-group design methods described in the study. A prediction is recorded before the test so that later explanation can be compared with the original reasoning. Group

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responsibilities organise planning, theoretical justification, measurement, processing and presentation, while individual responses remain necessary for assessment. The common requirement across these methods is a visible relationship between a decision and the physical evidence used to defend it.

Result 4. Six-Criterion Assessment of Process and Product

The assessment system distinguishes motivation, cognitive understanding, design, practical–technological activity, analysis and reflection. These criteria prevent a single successful measurement or a polished report from standing for the whole competence. Each criterion is associated with an observable action and a source of evidence (Table 3). The framework is used here as a methodological proposal, not as a psychometrically validated measurement instrument.

Table 3. Criteria of design competence and assessment evidence

Criterion	Observable action	Assessment evidence
Motivational	Engage with the problem and persist in investigating a difficulty.	Questions, participation and observation records.
Cognitive	Explain the physical basis and the purpose of the selected measurements.	Hypothesis, conceptual explanation and defence response.
Design	Develop a feasible plan and justify the apparatus and measurement procedure.	Design map, diagram and equipment rationale.
Practical–technological	Assemble and use the equipment safely and record measurements appropriately.	Observed performance and laboratory record.
Analytical	Organise results, interpret relationships and examine measurement limitations.	Calculations, tables, graphs and uncertainty discussion.
Reflective	Evaluate the work and justify an improvement to the investigation.	Self-assessment, conclusion and revision proposal.

The detailed assessment account distinguishes four qualitative levels. At the low, reproductive level, the student depends heavily on a prescribed procedure

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and has difficulty explaining its purpose. At the intermediate, inquiry-oriented level, the student completes standard actions with support but struggles to redesign the investigation when conditions change. At the good, constructive level, the student independently prepares a workable plan, processes evidence and defends a conclusion. At the high, creative level, the student also identifies a limitation, compares alternatives and proposes a justified improvement.

These descriptors are not numerical extensions of Etkina and colleagues' assessment scale [5]. Their use requires criterion-specific evidence and subsequent examination of rating consistency. Diagnostic tasks establish initial readiness; formative feedback addresses problems during planning and experimentation; and final assessment considers the completed investigation and its defence. Group products and individual explanations should be considered together so that collaboration does not conceal differences in understanding.

Discussion

The distinctive feature of the methodology is the connection between scientific inquiry and instructional organisation. Observation or simulation does not automatically produce design competence; students need to make and justify decisions about the investigation. Equally, a project without a clear physical model may become construction activity without adequate scientific explanation. The proposed sequence joins these requirements through a design map and documented process evidence.

Virtual and real laboratories contribute differently to that relationship. Comparing their results gives students an opportunity to examine the model and the practical measurement conditions. Reflection then turns the comparison into a decision about what to revise. This interpretation retains the importance of hands-on activity while avoiding the assumption that every investigation must use identical methods or the same digital resource.

Practical Recommendations

For each laboratory topic, the teacher should identify a decision that students can reasonably make independently and define the evidence needed to justify it. A design map should be reviewed before the experiment, with safety

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requirements kept explicit. Guiding questions can support students without replacing their plan. Time should be reserved for comparison, defence and revision, and the assessment criteria should be available from the start. Records of individual explanations should accompany group work so that feedback addresses the learner's actual difficulty.

Limitations and Directions for Further Research

The article presents a methodological system and illustrative tasks, not an experimentally established improvement in competence. It does not determine effect sizes, score thresholds, criterion weights or inter-rater reliability. The relationship between the four qualitative descriptors and existing scientific-ability instruments also remains to be examined. Further work should investigate task feasibility, the degree of student independence, the consistency of assessments and transfer of design decisions to unfamiliar laboratory problems. Claims about effectiveness require a documented study with appropriate outcome measures.

Conclusion

Developing design competence in general physics laboratories requires students to connect physical explanation with the planning, execution and evaluation of an investigation. The four-component model and five-stage sequence organise this connection through scientific inquiry, project activity and reflective assessment.

The unit-specific tasks show how a common methodological sequence can retain differences in physical content. The pendulum example illustrates the transition from following instructions to defending experimental choices. The six-criterion assessment framework makes both process and product available for examination. Its practical contribution is a structured basis for organising laboratory design activity; its diagnostic reliability and educational effectiveness remain subjects for empirical validation.

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