

Longitudinal trends of high school physics students' perceptions of experience, difficulty, and development in a long-term inquiry framework

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Response to the continuing call to integrate scientific inquiry activities into high school education has taken different forms varying in student ownership, physical setting, time span, and mentoring resources. Important issues are how students perceive central dimensions of their experience, and the extent to which the inquiry framework design serves to promote a sense of growth in the participants. The current research followed a group of 34 high school physics students who participated in the out-of-school Research Physics program over a 3-year period (2016–2019), gradually progressing from inquiry-oriented lab activities to an extended inquiry project under the guidance of teacher-mentors, within an instructional design of cognitive apprenticeship. The research focused on a set of 15 inquiry components, some directly related to experimental practices such as formulating inquiry questions, preparing and performing experiments, data processing using technological tools, others related to the scientific culture of presenting oral and written inquiry reports, and finally abilities of teamwork and self-regulation. Data regarding students' perceptions of three aspects—Experience, Difficulty, and Development with respect to the inquiry components, were collected at the end of each year, using self-report questionnaires. The analysis of longitudinal trends revealed several inquiry components for which significant changes occurred in the perceptions of the three aspects, which can be mainly related to the program design. The research hypothesis regarding the relationship between the three aspects was that the perceived Development would match the levels of the perceived Experience and Difficulty for all 15 inquiry components. The quantitative analysis revealed four groups of inquiry components, only two of which aligned with the hypothesis. The quantitative findings are explained based on program design and qualitative data about student effort and ways of coping and teacher-mentor scaffolding methods.

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I. INTRODUCTION AND RATIONALE

The call to integrate scientific inquiry in school education has continued in central position documents since the beginning of the 20th century [1] until present times [2–5]. According to the National Research Council (NRC) [2–4], inquiry is central to achieving the goals of science education, and students are expected to acquire scientific knowledge through a process involving inquiry components of asking scientific questions, planning and performing experiments, using appropriate data collection methods, and drawing conclusions through critical reference to the entire process. Prominent science education publications

have set out lists of such practices and proficiencies for k-12 science learners [6] and undergraduate physics students [7]. Recent international assessment policies echo the vision of a scientifically educated person as one who possesses procedural knowledge of the appropriate design for investigating a scientific question and the role of control of variables in experimental design [5].

Since the beginning of the 20th century, many programs have sought to teach science with greater emphasis on inquiry [8–15]. These programs placed different emphasis on two main goals. Learning “science by inquiry” meant that students performed inquiry activities that would help them discover fundamental principles of physics [16–18]. Alternatively, the goal was to increase the understanding of “science as inquiry” and engage students in the practices of scientific inquiry with a view to motivating them to pursue a scientific career and/or educating future citizens to understand and appreciate the methods and values of scientific inquiry [9,19–21]. The current research is guided

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by the recognition of the importance of setting recommended science and engineering practices as learning goals for students [22–25].

Engaging in the full range of inquiry practices requires lengthy work processes, dealing with open-ended problems, using advanced equipment, and the instructional guidance of teacher-mentors [11,23,26,27]. In reality, a wide gap exists between policy calls about the importance of inquiry-targeted instruction and the implementation of such teaching in traditional high school physics education culture, which prioritizes content knowledge, traditional problem solving, and confirmation experiments targeted at matriculation examinations [8,15]. As a result, high school physics teachers lack training and motivation for mentoring inquiry projects [11].

In view of the difficulty of establishing an inquiry-targeted learning culture in high schools, the science education community has sought to establish dedicated frameworks in which science students can participate in long-term meaningful inquiry. The literature [10,12,14,24,28–30] describes a wide range of implemented conceptions of student inquiry varying with respect to central goals and dominant practices:

- the inquiry extent in terms of duration and innovation in the scientific field.
- the extent of students' agency during the inquiry (from legitimate peripheral participation to full agency).
- the types of emphasized practices (from mainly empirical to comparing empirical findings with predictions of a theory-based mathematical model).
- the nature of teacher-mentor mediation via levels and timing of structuring and conferring agency.

The current research is situated within a local context in which an ongoing effort has taken place over the past decade to emphasize scientific research components in the instructional physics laboratory curriculum [2–7], as well as promoting designated frameworks for students to experience long-term inquiry. One such framework is the Research Physics program in which the constraints on time, equipment, and instructional resources have been considerably lifted [31–33]. Following are the central features of the program, with a fuller description in Sec. III. The three-year, out-of-school program starts with physics students in grade 10 and continues until the end of grade 12, parallel to the traditional, high school advanced physics course. The students are introduced to the “physics as inquiry” culture and methods during the Preparation stage [32] and spend the remaining 18 months working on an open-inquiry project dealing with a subject of their choice. Thus, the time constraint is decreased. The constraints on equipment and technical support are diminished by setting the instructional scene in designated, well-equipped laboratories where students and instructors can work assisted by professional technicians. The Research Physics program provides the participating students with

inquiry teacher-mentors, who are high school physics teachers trained in a designated professional development workshop and motivated toward implementing the open-inquiry approach [33]. Thus, the challenges in providing professional instructional guidance are reduced. In conclusion, the Research Physics program offers a learning environment where long-term, open-ended inquiry led by high-school physics students has the potential to flourish.

However, for students, the shift from the school-based norms, expectations, and culture regarding traditional instructional physics labs to this novel setting in which they are expected to think and behave in a manner approximating authentic research practices can be considered a “boundary crossing” challenge on many levels [34]. Perl-Nussbaum and Yerushalmi [32] dealing with the Research Physics program, extensively discuss students' perceptions of experimental practices across different settings, which they sometimes experience at the same time. In particular, they studied students' perception of the relevance of a set of practices that served as the Research Physics program learning goals during the introductory stage (regarding the investigation process, engagement in the scientific community, and self-regulation in the complex research process) and found that practices that had a shared meaning in both cultures were considered relevant.

Smoothing the transition across the rough boundaries dictates a gradual and scaffolded development of experimental practices and perceptions along the range between traditional instructional physics labs and long-term investigation of an open problem of the students' choice. On the one hand, a process of “learning to inquire by performing open-inquiry” is required. On the other hand, scaffolding (structuring and problematizing) is necessary to reduce the students' struggle with the open problem by the guidance of a teacher-mentor [35].

As the program unfolds, students progress from inquiry-oriented instructional labs to an extended research project guided by teacher-mentors, implementing a wide range of inquiry practices. Along this path, they perform inquiry practices, invest effort in dealing with difficulties, and gain a sense of development and growth. This long-term evolution of the students' identity as novice researchers raises several pertinent questions. How are students' perceptions of experiencing and struggling with different components of the inquiry and their perceived development related to the different stages in the program? How are students' overall perceptions of experience and difficulty related to their perceived development regarding different components of the inquiry?

Answering these questions can inform the design of inquiry learning progressions [7,36] and in particular explicate the role of teacher-mentors in scaffolding students' performance and conceptions along the trajectory between the introductory and the final Research Physics program stages.

II. REVIEW OF THE LITERATURE

A. Open-inquiry: Features and components

Dewey [37] saw inquiry as the asking of a question and the search for valid ways to answer it. Learning through open-inquiry involves active, experiential, and in-depth learning related to science issues that the students find relevant and interesting. This approach places the student in the center and encourages a meaningful learning process characterized by constructing knowledge through the search for solutions to problems [38]. From the beginning of the open-inquiry process, the student (rather than the teacher) is required to formulate research questions, set the investigation goals, carry out the investigation independently, planning and performing experiments, and seeking relations between the findings. Independently proposing an inquiry question is in itself the key to open-inquiry [23,24], for which the outcomes are not necessarily known to the student and possibly neither to the teacher [23]. Higher levels of inquiry will be achieved as the student becomes more independent and performs activities mimicking those undertaken by research scientists [39].

The inquiry process involves many components that have been defined in prominent science education publications [4,6,7] under a variety of names such as methods, processes, practices, skills, and proficiencies. NRC (NGSS) [6] lists eight broad science and engineering practices, which are not isolated from each other, but rather overlap and interconnect: (i) Asking questions, (ii) developing and using models, (iii) planning and carrying out investigations, (iv) analyzing and interpreting data, (v) using mathematics and computational thinking, (vi) constructing explanations, (vii) engaging in argument from evidence, and (viii) obtaining, evaluating, and communicating information. The AAPT recommendations [7] detail the expected focus areas of the learning outcomes of undergraduate student lab activities: Constructing knowledge, modeling, designing experiments, developing technical and practical laboratory skills, analyzing and visualizing data and communicating physics. Duschl and Bybee [40] suggest a 5D model for the goal of Planning and Carrying Out Investigations: Deciding, Developing, Documenting, Devising, and Determining. Holmes and Smith [41] describe undergraduate experimental physics skills that include technical and practical skills (set up equipment, analyze data, writing, and communication), cognitive decision-making skills (what and how much data to collect, how to minimize uncertainties, or how to interpret results), and metacognitive skills.

For the purpose of the current research, we have adopted the term “inquiry components” for the practices and processes in which students engage during their inquiry activities and projects. Our list of inquiry components includes among others: “locating information sources,” “phrasing questions or goals,” “planning an experiment,”

“performing an experiment,” “data processing,” “building content knowledge,” “drawing conclusions,” “written reporting on the inquiry,” “self-regulation,” and “teamwork with the partner.”

The list of components does not necessarily express chronological order. In reality, the inquiry process rarely follows a linear predetermined sequence, but it can be divided into phases and components with reciprocal interaction and the transition between them is networklike. During the inquiry, project phases and components may be revisited due to unexpected findings driving a reconsideration of basic hypotheses [10,42,43].

B. The open-inquiry scene: Challenges faced by teachers

Clearly, teachers have a decisive impact on the implementation of inquiry by students. To implement the inquiry approach, teachers must integrate new practices into their traditional teaching. In particular, they must shift from top-down management, where they dictate what to research and how to perform the investigation, to an approach that includes listening to students’ ideas and guiding them about selecting investigation topics and shaping the appropriate inquiry procedure. The switch from top-down student management to a guiding-coaching mode presents a true revolution in the teacher’s role, for which traditional teacher training courses provide little preparation [11].

Alongside the importance of open-inquiry and the many recommendations to integrate teaching according to the inquiry approach, it is important to address the challenges and difficulties teachers face when they incorporate inquiry-based teaching into their traditional instruction [8,15,23,44]. High school physics teachers operate under several external constraints: lack of time, lack of equipment and materials, and the need to prepare students for the final high school examinations, which challenge their ability to integrate inquiry-based teaching. Teachers may face additional challenges related to their perceptions about science in general and inquiry in particular, their apprehension of changing their role from traditional teacher to inquiry leader, and their insufficient training and expertise in teaching through inquiry [8,11,44–49].

The main factors influencing teachers’ motivation and ability to teach ‘science as inquiry’ are their personal views about the pedagogical aspects of the inquiry process [48]. Teachers who prefer to control what happens in the classroom, structuring knowledge and drawing conclusions, will find it difficult to integrate open-inquiry [49]. Moreover, teachers may be anxious about coping with ambiguity, uncertainty, and unexpected outcomes, all of which are natural features of open-inquiry [50]. Teachers may believe that they are expected to provide answers to all students’ possible questions that may arise in the inquiry process, while the teacher might not know the answer. Teachers may be concerned that their lack of advanced scientific

knowledge might affect students' esteem toward them [15]. To prevent such situations, teachers are likely to avoid encouraging open-inquiry in their classroom [45,51]. This is especially prominent among teachers who lack experience in the management of inquiry and generally lack understanding about the inquiry process [46,47].

Studies note that a majority of teachers lack experience in genuine scientific research, as well as knowledge and understanding about the nature of authentic inquiry. It is doubtful whether they themselves had experienced inquiry in their scientific training [11,18]. Therefore, it is not surprising that teachers are concerned about integrating open-inquiry into teaching and find it difficult to help students with asking meaningful questions, planning experiments, drawing conclusions from measurement findings, and implementing strategies for managing teamwork [18,46,47].

Appropriate training is required to equip science teachers with the knowledge, skills, and role conceptions needed to become proficient inquiry mentors. Such training is often lacking and needs to be implemented via designated long-term professional development programs in which teachers perform authentic inquiry under the mentorship of experienced researchers [11,47,49,52,53].

C. Open-inquiry: Benefits and challenges for students

Students who engaged in independent open-inquiry were exposed to and reached content areas beyond the range of traditional classroom science and acquired considerable knowledge related to the problem they addressed [22]. Students who were more active in planning experiments and who applied the knowledge and skills they had acquired, attained high achievements and internalized the meaning of inquiry, which contributed to reinforcing their self-confidence [54]. Students' experience in performing inquiry and explaining the results strengthens their feeling of ownership toward the process and achieved products, thus enabling the students to feel part of a scientific community, bringing the learners closer to the true world of the scientist and potentially helping them understand the nature of science [23]. The more independent students were in the inquiry they performed, the more they developed positive attitudes toward science [55]. In addition, the open-inquiry approach creates learning opportunities that foster the development of skills usually underrepresented in traditional learning, such as becoming an independent learner, and employing higher-order thinking skills, expressed by asking questions, formulating inquiry questions and hypotheses, planning experiments, oral discussion, and sharing knowledge with peers [11,22].

The integration of inquiry into classroom teaching and learning also presents students with considerable challenges and difficulties. The open-inquiry process shifts students from a position of listening and absorbing, remembering and understanding toward an active process

of constructing new knowledge, through the implementation of independent thinking while searching for an answer to the inquiry question [56]. The student is required to adopt the role of a constructor of knowledge, who initiates the inquiry and thinks critically, rather than the traditional role of repeating information, subordinate to the teacher's authority [44]. The students are required to identify missing information, classify, filter, organize, edit, and process information, validate it against previous knowledge, evaluate it critically, draw conclusions, and continue iteratively until they find a well-founded, creative solution [2,3,24]. At the top levels of inquiry, students are involved in solving the problem, taking responsibility for planning the inquiry process and for their learning, and are required to think critically about their understanding of concepts and the process they perform [23–25,57].

According to Sandoval and Reiser [25], many students find it difficult to conduct independent inquiry. Students who are required to perform inquiry activities sometimes feel confused and frustrated since the performance instructions are not clear to them or due to their concern about coping with failure [23,45]. Some are apprehensive about dealing with situations of uncertainty, as the inquiry results are not known in advance or with other unexpected problems, issues, and dilemmas that arise naturally during the inquiry process for which they lack ready answers. Sometimes there are no unequivocal answers and the students must independently develop a strategy leading to appropriate answers [23,24].

While there is abundant evidence that engaging in inquiry may be fraught with student anxiety and reluctance, other researchers claim that coping with these concerns may serve as a lever for learning. It was found that failures led to the acquisition of additional inquiry skills and to the development of higher-order thinking abilities, such as critical assessment and intelligent analysis, phrasing questions, searching for creative solutions, and the ability to autonomously find answers [10,28,29]. Thus, it seems that while experiencing open-inquiry presents students with many difficulties and challenges, it has the potential to contribute to the development of knowledge, skills, and favorable attitudes.

III. CONTEXT—RESEARCH SETTING

A. Design principles of the Research Physics program—The cognitive apprenticeship paradigm

Since the transition from traditional, teacher-led instruction to long-term, open-inquiry presents a significant change in the teaching-learning culture and in the respective roles of teachers and learners, the management of the required shift in responsibility and initiative is of vital importance [9,11,20]. The design of an inquiry curriculum must take the considerable cognitive load imposed by open-inquiry into consideration [10].

Some researchers [11,22,23] recommend a gradual process in which students first perform structured inquiry, leading to expected outcomes. During this initial stage, students may be introduced to new techniques and acquire and improve inquiry practices. Following the initial stage, a gradual increase in student independence coupled with reduced teacher guidance occurs regarding key inquiry components. Students may be called to select inquiry topics in which they are interested, to formulate the problem and the investigation goal, to decide on the inquiry method, and to carry it out independently [11,24].

One approach for facilitating learning of a complex domain is the cognitive apprenticeship paradigm [58] according to which learners should be afforded suitable scaffolds to facilitate functioning within their zone of proximal development [59].

In general, the developers of the Research Physics program adopted the principles of cognitive apprenticeship, placing learners in authentic situations in which they work with teacher-mentors as accomplished experts [58]. The teachers mentor the students, guide the learning process, and focus on the students' development and the evolving project product [35,58,60]. According to Collins *et al.* [58], in the model of cognitive apprenticeship, the learner accepts the commitment to the learning process, actively experiences the performance of assignments, cooperates with peers, and participates in a continuous dialogue with the teacher-mentor.

The cognitive apprenticeship instructional model includes 3 core methods—modeling, coaching, and scaffolding [58]. Modeling involves an expert performing a task while externalizing cognitive processes so that students can observe and build a conceptual model of the required processes for accomplishing it. Coaching and scaffolding consist of observing students while they carry out a task and offering hints, feedback, and support aimed at bringing their performance closer to expert performance. Finally, cognitive

apprenticeship leads to fading—gradually reducing support, empowering students to continue independently [35,58,61]. Reiser [35] discerns two types of scaffolds, namely structuring and problematizing. Structuring involves ways of simplifying complex tasks by dividing them into a sequence of subtasks as well as modeling or making thinking visible. The coaching process should also involve a problematizing strategy, helping students notice something that requires questioning or critically examining a concept, idea, or situation that may not be immediately obvious, in order to highlight its complexities, contradictions, or potential issues, leading to challenging the students and encouraging a deeper understanding of a topic.

Within the Research Physics program, cognitive apprenticeship was implemented by teacher-mentors and the program staff. For example, modeling expert inquiry practices such as controlling variables, providing feedback for drawing conclusions from graphed experimental data, and directing students' attention to gaps between the theory and experimental conclusions.

B. The learning sequence of the Research Physics program

The students experienced a 3-year learning sequence (2016–2019), divided into 3 stages (Fig. 1). During the Preparation stage (10th grade), the 54 students of the regional class worked in small teams with changing partners, under the supervision of two expert teachers. During the Intermediate and Final stages (11th and 12th grades), a selected group of 34 students worked on their inquiry project in fixed-pair teams and with permanent teacher-mentors. In the following, we present the sequence of inquiry activities in each of the stages (see Appendix B, left column) and the scaffolding provided by the program structure and the teacher-mentors.

During the Preparation stage (tenth grade), the students met for biweekly, four-lesson sessions, engaging in

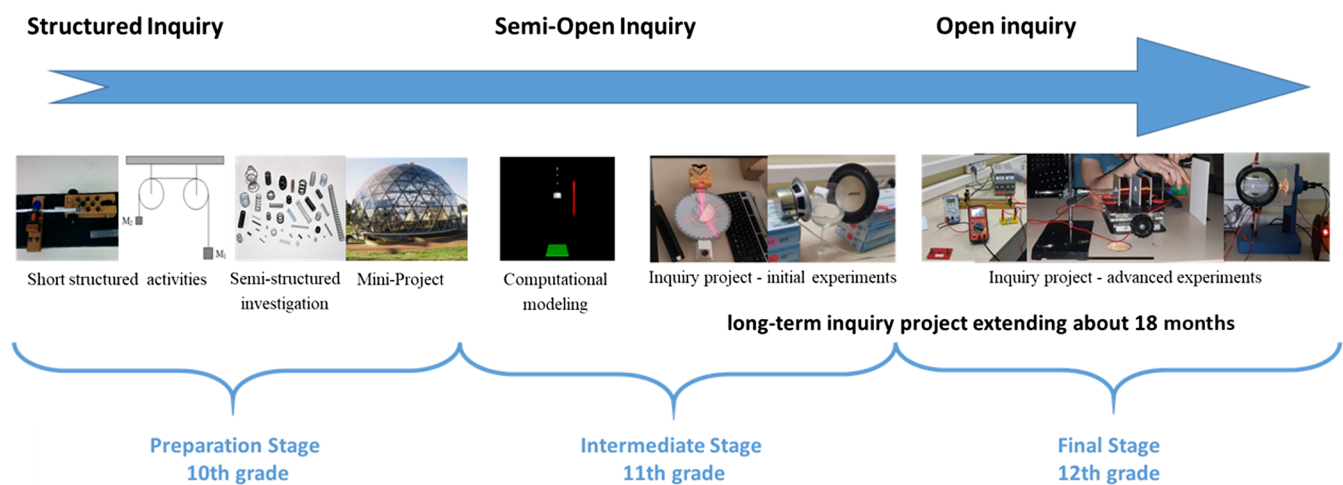


FIG. 1. The Research Physics program learning sequence—from structured inquiry activities to an open-inquiry project.

relatively short (one to two sessions) structured activities. Each activity emphasized specific inquiry practices and/or measurement devices. This led to performing a four-session miniproject involving semiopen-inquiry on a variety of science playground systems. Perl-Nussbaum and Yerushalmi [32] provide further detailed information about the inquiry activities during the tenth grade.

This stage involved developing experimental practices by structuring and problematizing in restricted inquiry activities with reduced cognitive load. The teacher-mentors carried out scaffolding activities, which helped in structuring the problem-solving tasks, as well as problematizing them. One such example can be seen in the first activity “a trolley moving at constant speed” [32]. Contrary to traditional school laboratory activities, where the experiment setup and instructions for data collection are given in detail, the Research Physics participants were required to first design the experimental setup to achieve constant motion, perform measurements with unfamiliar equipment, and decide on the appropriate representation of the collected data.

In the Intermediate stage (11th grade), the regional class was reduced to 34 students, meeting weekly for 4-lesson sessions. For the first nine sessions, the students were introduced to computational modeling using Vpython software [62] for building models of physical phenomena. This was followed by a 12-session section in which team pairs selected an inquiry topic and worked with a designated teacher-mentor on preparing a proposal for open-ended inquiry projects in various fields in physics, such as mechanics, electricity and magnetism, thermodynamics, optics, and waves (Appendix A).

During the final 12 sessions of year 11 student teams performed preliminary explorations and selected investigation paths to better understand the researched phenomenon. The Intermediate stage concluded with a report summarizing the initial explorations, which constituted the basis of the final project.

In the Final stage (12th grade), the class of 34 students continued meeting weekly for 4-lesson sessions. The team pairs guided by their teacher-mentors continued performing new and advanced experiments, extensively exploring their chosen topic, both theoretically and experimentally, to gain answers to their inquiry questions. This stage concluded with the construction of a final project report, internal evaluation, and an external Ministry of Education examination.

During the two advanced stages (Intermediate and Final), scaffolding was implemented by the teacher-mentors who formed an inquiry community advised by the Research Physics program leading team. The level of implementation varied according to the teacher-mentors' personal abilities and depended on their own knowledge of physics content, inquiry methods, measurement, and analysis technology as well as their role perception as

inquiry mentors and physics teachers. Most teacher-mentors scaffolded the acquisition of advanced theoretical knowledge by providing references to physics books or articles. In one rare case, the teacher-mentor enlisted in an advanced academic course, and the student team joined him. Structuring was implemented by setting a timetable and standard format for performing specific steps in the open-inquiry project. Problematising was implemented by the requirement to acquire advanced theoretical knowledge, improve experimental design and measurement, correlate empirical findings with theoretical modeling, identify error sources, prepare presentations, engage in peer review, and revise products.

In conclusion, true to the cognitive apprenticeship paradigm, the Research Physics program sequence enabled students to experience inquiry practices in different types of activities in the field of physics, steadily increasing in their scope and gradually moving from short, semistructured activities to long-term open-inquiry. As the complexity and challenge of the activities increased, the students were coached by teacher-mentors, providing support for their independent work. Scaffolding was gradually faded by transferring greater autonomy and responsibility to the students.

IV. RESEARCH GOALS AND APPROACH

An ongoing formative evaluation of the Research Physics program was carried out during the first program cycle (2015–2018), which resulted in changes implemented during the second cycle (2016–2019), following lessons learned. Thus, the current research, which took place during the second cycle of the Research Physics program, can be framed within the design-based educational research approach [63–65].

Our aim is to describe and analyze the participating students' perceptions of learning in a long-term, open-inquiry environment, designed along the cognitive apprenticeship paradigm. In particular, our goals were to discover longitudinal trends and relationships among student perceptions using quantitative and qualitative research methods.

Student engagement with the Research Physics program involved 3 years of doing—struggling—growing [10,28,29]. Correspondingly, we named the following three student perception aspects:

- Experience—performing the designed learning activities and inquiry practices
- Difficulty—dealing with the need to surmount barriers and master unfamiliar ways of thinking and acting in new content domains
- Development—transforming from novices to more cognitively, affectively, and practically accomplished researchers.

The current research is intended to give students a voice to express their perceptions of the Experience, Difficulty,

and Development aspects as related to a list of inquiry components. Summative questionnaires (Appendix C) were administered toward the end of each of the three Research Physics program stages, in which students were requested to rate their perceived levels of Experience, Difficulty, and Development for a list of inquiry components (ICs).

Our research focused on inquiry components which students rated highly in each aspect, by indicating “considerable level” in the questionnaire. We offer the following possible meanings of perceived considerable level for each aspect:

- considerable Experience: Frequent engagement in performing the IC; estimate of much time spent in performing the IC; awareness of repeatedly performing the IC
- considerable Difficulty: Sense of struggling to achieve efficacy; feeling challenged; awareness of frustration in attempting to perform; feeling of being unable to perform or needing or requesting help
- considerable Development: awareness of becoming more proficient and skilled, being able to select a variety of action paths, mobilize resources, and perform more efficiently; feeling of progress from novice to expert in one’s thoughts and actions; feeling of becoming more confident; awareness of the ability to reflect on one’s thoughts and performance and reconstruct one’s beliefs when necessary; perceiving oneself as becoming a member of the inquiry community of practice.

This research occurred in the context of the unique Research Physics program, which offered a constraint-reduced inquiry framework for high school physics students. The findings may contribute to the knowledge and understanding of the evolution of student perceptions and the relationship between perceived considerable Experience, Difficulty, and Development related to a variety of inquiry components. Moreover, the research findings have the potential to inform and improve the design of this, and similar, interventions by reflecting the participating students’ perceptions of their long-term lived experience and indicating “what worked” and “what required changes”. Beyond the relevance of this research’s findings to the Research Physics program, it shines a light on the complexity of learning to perform a long-term complex inquiry project in a supportive yet demanding framework and offers methods for investigating the process. Thus, it has the power to enrich the research domain of learning beyond the traditional classroom.

A. Research questions and research hypotheses

The current research focuses on two research questions related to students’ perceptions during the 3-year process.

RQ1: What changes occurred in students’ perceptions of Experience, Difficulty, and Development related to a set of

inquiry components, as measured at three stations along the Research Physics program sequence?

The hypothesis for RQ1 is that in each of the perception aspects (Experience, Difficulty, Development), there will be an increase regarding the inquiry components along the program timeline, associated with the increased involvement of the students with the inquiry components, as they progress from the Preparation to the Intermediate and Final stages of the program. However, the relevance of an inquiry component at the different stages, especially close to the questionnaire date, may affect the trend.

RQ2: How was students’ perception of their Development related to their perceptions of Experience and Difficulty with respect to a set of inquiry components along the 3-year process?

The hypothesis for RQ2 is that the degree of perceived Development regarding inquiry components will be related to the degrees of perceived Experience and Difficulty for these components. In particular, the more the students engaged in the inquiry components and the more they coped with related difficulties, the degree of perceived Development is expected to increase, as evidenced in previous studies [28,29].

V. METHODOLOGY

A. Research population

The research population consisted of 34 high school students (12 girls and 22 boys) taking advanced-level physics in grades 10–12, who participated in the 2016–2019 regional class of the Research Physics program. In 2016, the program recruited 54, 10th-grade students, originating from 5 schools of varying socioeconomic and academic levels from central and outlying areas. Some of the students had studied physics in accelerated streams in grades 7–9 while others had taken regular integrated science classes. The students had self-elected to participate and were recommended by their physics teachers (based on a short period of acquaintance) as having the required ability, motivation, and interest to engage in physics inquiry. A preliminary questionnaire showed that none of the students had previous open-inquiry experience. The students’ participation involved 4-lesson afternoon sessions at the science education institution. Transportation and tuition were funded by local authorities and the Ministry of Education. Successful graduation from the Research Physics program entitled the students to an extra matriculation credit, accepted by institutions of higher education.

At the end of the first year, a group of 34 students were selected by the program staff to continue to the following stages based on their level of scholarship and commitment rather than on achievements. This group persisted in the Research Physics program parallel to their school and other commitments, which attests to their resilience in coping

with the nontrivial tasks involved in open-inquiry throughout the 3 years. However, there was considerable variability in their school grades, inquiry project types, and inquiry performance.

B. Ethical issues

The current research complied with the ethical requirements for research involving school children aged 15–18 within an educational setting. The Chief Scientist of the Ministry of Education approved the first author's application for collecting research information about students participating in the 2016–2019 Research Physics program for the purpose of her doctoral studies. All the students' parents signed informed consent forms and all the students agreed to participate in the research and continue as research subjects until they graduated from the program.

C. Research methods

The current research employed a mixed-methods research approach, aimed at portraying the students' perception of the processes they underwent during the 3-year Research Physics program. Elements of quantitative and qualitative research methods were combined for data collection and data analysis [66,67]. The main sources of quantitative data were self-report questionnaires administered toward the end of the Preparation, Intermediate, and Final stages of the Research Physics program. Qualitative data were collected from the open-ended questions in the questionnaires, as well as from the observations performed by the first author throughout the program sequence and the analysis of student-submitted products. Further details will be described in the Research instruments section.

The integration of quantitative and qualitative approaches offers a rich picture of the discussed phenomena and provides an in-depth view of the researched environment. The qualitative research method serves to illustrate and clarify the results of the quantitative method, helps to characterize the experiences, and enriches the interpretation of the quantitative research [68,69]. Moreover, the use of more than one method may overcome biases and weaknesses of other methods, thus contributing to the validation of the findings and the research conclusions [69,70].

D. Research instruments

1. Questionnaires: Design and procedure

The main research instruments were questionnaires composed of closed as well as structured open questions (Appendix C). For the purposes of the current research, we shall describe only the relevant two main sections of the questionnaires—part B and part C.

Part B starts by directing the student to the table of inquiry components and continues with two questions

intended as an advance organizer for student response. The sentence following the questions instructs students where and how to respond. For each inquiry component, students were instructed to tick their perceived levels of Experience and Difficulty in two of the six adjacent columns. Students indicated their perceived levels of Experience and Difficulty related to each inquiry component, on a scale of 0 = not at all, 1 = a certain level, 2 = a considerable level. This condensed scale served to highlight dominant student perceptions. Our intention was to elicit the “considerable” response option. The 0 and 1 options were provided to ensure that “considerable level” was understood as the strongest degree of perception. Below the table, students were invited to add additional inquiry components, describe the related levels of Experience and Difficulty, and comment about the support they had received.

Part C included two structured open questions to which students were instructed to respond verbally in the provided lines:

1. Students were required to choose at least two of the inquiry components that involved considerable Difficulty and describe how they had coped with the challenges.
2. Students were required to choose 2–3 of the inquiry components in which they felt they had experienced considerable Development and describe how they had developed.

These summative questionnaires were administered at three significant points in time (stations) along the Research Physics program. Each station will be named according to the corresponding program stage:

- station 1—at the end of the Preparation stage, just prior to the submission of the “miniproject” report (May 2017, $N = 27^*$)
- station 2—close to the end of the Intermediate stage, just prior to the submission of the interim project report (April 2018, $N = 33^*$)
- station 3—close to the end of the Final stage, just prior to the submission of the final project report (May 2019, $N = 34$)

Note: *Some participants were absent on the given day.

Prior to filling out the questionnaires, the students received an explanation about the purpose of the research and its importance. It was made clear to them that the research would maintain confidentiality, the information provided by the questionnaires was for research purposes only, future publications would not include any identifying details, and they had the right to withdraw from the research at any time. This was in order to reduce the natural concern of some of the students about expressing themselves freely, fearing that their responses would be transferred to others, such as their teacher-mentors or other students, and to raise their awareness of the importance of answering the questionnaire honestly and seriously.

Observation of student behavior during the three questionnaire administration sessions indicates that the students filled the questionnaires fully, in a relaxed and serious manner, without requesting explanations about the inquiry components. Although the questionnaires did not explicate the meaning of each inquiry component, it would seem that the meaning was quite consistent across the student sample. The meaning of many inquiry components can be understood literally, e.g., choosing the topic for the project, performing precise measurements, writing a presentation for reporting on the project, and presenting orally to peers and teachers. Many of the inquiry components were explicitly introduced and used during the Research Physics program sessions, e.g., focusing the inquiry question, isolating variables, linking theory to the experiment findings, and performing peer assessment. These terms were an integral part of the discourse in the Research Physics program.

A necessary condition for answering the questionnaires authentically, rather than out of social pressure or social desirability, is a certain degree of maturity and self-reflection which may be lacking in students aged 15–18. Nevertheless, it is important to elicit students' reactions and give students a “voice,” thus adding authentic participant information and providing a basis for bottom-up explanations about the research field.

2. Observations: Gaining students' perspective of physics inquiry

Throughout the 3-year Research Physics program, the first author carried out observations of the student teams and their teacher-mentors as they worked on their varied inquiry projects. The observations were conducted following the ethnographic research paradigm [71–73] and all documentation was in writing.

The Research Physics program can be seen as an ecology consisting of members belonging to three different “classes” in the “learning to become a physics researcher” space: The program staff, the teacher-mentors, and the students. The observer-researcher was interested in gaining an authentic understanding of the students' behavior, discourse, motivation, difficulties, concerns, mindsets, relationships, reasoning, etc. To achieve the desired authentic picture, the researcher decided on unstructured, semi-participatory observations of student teams working on their inquiry projects. The students knew the researcher as a physics teacher with an interest in open-inquiry, accepted her presence as a natural part of the educational environment, and seemed unperturbed by her observations.

Some of the documentation will serve the current research by explaining or justifying the quantitative results of the analysis of the questionnaires that sampled student perceptions and views at three discrete points many months apart.

E. Data analysis

1. Establishing the list of inquiry components

The list of inquiry components evolved by a process of expansion between the program stages followed by a contraction prior to the data analysis. At the first research station (end of the Preparation stage), the questionnaire listed seven representative inquiry components. This list was expanded to 27 inquiry components in the questionnaires administered at the end of the Intermediate and Final stages (Appendix C). The additional inquiry components corresponded to practices that were included as the students engaged in more complex and open-ended inquiry.

For the purpose of data analysis, a final list of 15 inquiry components was created using a mapping procedure. One or more inquiry components were united under a single inquiry component with an inclusive name (Appendix D).

Table I presents four central inquiry phases and the related inquiry components for each phase. The seven inquiry components in *italics* were included in the questionnaires at all three research stations. The central inquiry phases we defined provide a general framework for conducting inquiry and can be adapted to various inquiry activities [10,43]. The order and nature of these phases can change depending on the type of investigation or problem being addressed. The final list of inquiry components covers a wide range of content-related, practical, inferential, intrapersonal, and interpersonal practices and proficiencies expected of students involved in long-term, open-inquiry and corresponds to central inquiry

TABLE I. Central inquiry phases and related inquiry components.

Central inquiry phases	Inquiry components <i>Italics</i> = included in all three questionnaires
Preparing and planning	Choosing a topic or investigation directions Locating information sources <i>Phrasing questions or goals</i> <i>Planning an experiment</i>
Performing and analyzing	<i>Performing an experiment</i> Using technological aids and a computerized laboratory <i>Data processing</i>
Constructing knowledge and modeling	<i>Drawing conclusions</i> Building content knowledge Building a theoretical model
Communicating and management	<i>Written reporting on the inquiry</i> <i>Oral reporting on the inquiry</i> Self-regulation Teamwork with the partner Teamwork with the other peers in the broad group

components indicated in relevant science education publications [3,7,32,40,42].

2. Defining summary measures of perceived Experience, Difficulty, and Development

For each inquiry component, we wished to obtain a summary measure of the student's perceptions of the dominant effect regarding the three aspects—Experience, Difficulty, and Development, at each research station. To serve this purpose, we computed the relative frequency of votes of “considerable level” for each of the aspects, for each of the inquiry components, while disregarding votes of 0 or 1.

The “relative frequency” was defined as the percentage of the votes of a considerable level out of the total number of students who responded to the questionnaire at each station. For example, the relative frequency for the Difficulty aspect of “phrasing questions or goals,” at the Preparation station was 52%. At this research station, 27 students responded to the questionnaire, and 14 of them voted considerable Difficulty for this inquiry component.

The students' responses to the questionnaires provided data for the computation of the relative frequency. For each inquiry component in the given list, the students marked the perceived levels for the aspects of Experience and Difficulty in the questionnaire form, which enabled straightforward calculation of the frequency of “considerable” votes. The frequency for the Development aspect was elicited through the open question in part C of the questionnaire: “Choose from the list above 2–3 components in which you think you have developed considerably during the program. Please describe.” To obtain the frequency for the Development aspect, per inquiry component, the students' answers to this question were sorted into the set of inquiry components relevant to the given research station. The frequency for each inquiry component was divided into the number of participating students to calculate the relative frequency. For example, the relative frequency for the considerable Development aspect of “phrasing questions or goals” at

the Preparation station was 37%. Of the 27 students responding to the questionnaire, ten included “phrasing questions or goals” as an inquiry component in which they felt considerable Development.

A second summary measure was required for the purpose of rating and comparing the relative frequencies of inquiry components. For each aspect, the “mean relative frequency” (mrf) was defined as the average relative frequency (%) over all the inquiry components for the given research station (7 inquiry components in the Preparation station and 15 inquiry components in the Intermediate and Final stations). The mean relative frequency formed a reference standard for rating the relative frequency of a certain inquiry component as being above or below the mean relative frequency at each station and for each aspect (Experience/Difficulty/Development). The mean relative frequency is a measure of central tendency that takes all the relevant data into account and provides a more representative view of student votes, compared to the relative frequencies themselves. For example, the mean relative frequency for the Experience aspect at the Preparation station is 63% (which means that on average, 63% of the students marked their perception of considerable Experience per inquiry component at the Preparation station). By comparison, the relative frequency of 89% for the Experience aspect of “phrasing questions or goals” at that station is much higher than the mean relative frequency, and the relative frequency of 7% for the Experience aspect of “oral reporting on the inquiry” at the same station is much lower.

Table II summarizes the structure of the processed data. The research stations are on the first row. The second row shows the three aspects (Experience, Difficulty, and Development) for each station. In the rows related to inquiry components, each cell presents the relative frequency (%) of the students' ratings of considerable level for the specified aspect (Experience, Difficulty, and Development) and research station (Preparation, Intermediate, and Final). The bottom row shows the mean

TABLE II. Structure of the research data quantitative analysis. For each research station: 1. For each inquiry component the relative frequency* (%) regarding the Experience, Difficulty, and Development aspects. Sample values of relative frequencies for the inquiry components “phrasing questions or goals” and “planning an experiment” are shown. 2. Values of the mean relative frequency** (%) for each aspect.

Research stations	Preparation			Intermediate			Final		
Aspect	Experience	Difficulty	Development	Experience	Difficulty	Development	Experience	Difficulty	Development
Inquiry components	Relative frequencies (%) of ‘considerable level’ perception for each aspect								
Phrasing questions or goals	89	52	37	82	28	49	91	21	50
Planning an experiment	67	15	19	79	12	21	88	24	21
Mean relative frequency (%)	63	23	24	75	14	29	79	13	33

*Percentage of students reporting ‘considerable level’ for an aspect related to an inquiry component at a research station.

**Average of all relative frequencies for a given aspect of overall inquiry components at a research station.

relative frequencies (%) for each aspect and each research station.

The research data structure presentation enables tracking longitudinal trends for each inquiry component and aspect and identifying inquiry components for which the relative frequency (%) for an aspect and research station is equal to or exceeds the corresponding mean relative frequency.

3. Quantitative and qualitative data analysis procedures

The descriptive quantitative analysis procedures for obtaining summary measures (relative frequency and mean relative frequency) of the students' perceptions of dominant effects regarding the three aspects, for each inquiry component at each research station, were described in the previous subsection.

Inferential quantitative data analysis was performed using the chi-square (χ^2) test for independence to check the significance of changes in the relative frequency of the Experience, Difficulty, and Development aspects for the inquiry components between pairs of research stations: Preparation vs Intermediate, Intermediate vs Final, Preparation vs Final. The level of significance was set as $p < 0.05$. The quantitative statistical findings were cross-checked against qualitative data about the Research Physics program to interpret and justify the results and generate a developmental view of the changes between different stages of the 3-year Research Physics program.

Additional data analysis resulting in an integrated rating for each of the 15 inquiry components over the 3 research stations will be detailed in the context of the findings for research question 2.

The qualitative analysis of students' answers to the open questions in part C of the questionnaire was based on the classification of verbal data, mainly using Chi's paradigm [74]. The verbal data were sorted into the inquiry components listed in the questionnaire and related to the students' perceptions of considerable Difficulty and Development. For example, the following verbal response in the Intermediate research station regarding considerable Difficulty in the "data processing" component indicates the contribution of teamwork and effort to overcoming difficulties in the inquiry process: "...it was hard to reach more 'complicated' data like acceleration, by ourselves. But my partner and I succeeded by thinking which data should be collected, and we learned together how to process the data." The following verbal response in the Preparation research station regarding considerable Development in the "data processing" component indicates the awareness of acquiring practical and cognitive skills: "I developed in 'data processing'—I learned to create graphs in Excel and I developed in how to look at the graph."

Thus, the quantitative findings were augmented with related qualitative verbal data to generate a richer picture explicating the students' viewpoint regarding what they performed, how they struggled with obstacles, and the

extent they transformed into more accomplished inquirers. Appendix E illustrates how emergent insights were derived from verbal data regarding the Difficulty and Development aspects of two inquiry components.

Students' verbal data were also analyzed to address the validity issue regarding the meaning students attributed to the Experience, Difficulty, and Development aspects. This analysis served to ascertain that students' facets of the meaning of the three aspects matched those we defined (Sec. IV, paragraph 3). Examples of corresponding students' comments are presented in Appendix F.

In summary, the verbal data analysis yielded information of four kinds:

- quantitative information related to the inquiry components for which students perceived considerable Development, as described in Sec. VE 2.
- information describing experiences and feelings throughout the inquiry sequence from the students' viewpoint and the identification of emergent insights regarding their difficulty or development and the role of teacher-mentors.
- facets of students' interpretation of the Experience, Difficulty, and Development aspects.
- several new inquiry components generated bottom-up from the first station questionnaires, such as "teamwork"

A comprehensive description of the qualitative analysis of verbal data collected by the questionnaires and observations (such as detailing and defining the students' difficulties and developmental aspects related to the various inquiry components) exceeds the scope of the current paper.

VI. FINDINGS AND PRELIMINARY INTERPRETATION

The two defined summary measures provided a quantitative method allowing us to address the two research questions: Examining changes over time and finding relationships between the perceived Experience, Difficulty, and Development aspects for given inquiry components. This quantitative analysis served to highlight general trends and relationships that would not have emerged from a purely qualitative analysis of student verbal data.

It is not our intention to provide an objective evaluation of students' difficulties and development but rather to attend to the students' own evolving perceptions as they participated in the long-term Research Physics program. In our report, we attempt to relate the students' perceptions to the structure of the intended program and the manner it evolved in the complex reality of diverse students, teacher-mentors, and inquiry projects.

Due to the three-dimensional variable space (research station, aspect, and inquiry component), the visual representation of the data is divided into 3 separate graphs with

the vertical axis scale of 0%–100% and the horizontal axis indicating the 3 research stations. Each inquiry component is represented by a unique icon (Fig. 2).

A. Research question 1

What changes occurred in students' perceived considerable Experience, Difficulty, and Development related to a set of inquiry components, as measured at three stations along the Research Physics program? In addressing this question, we limited the inquiry components to the subset of seven core components that were common to the questionnaires at all three stations. These inquiry components represent the four central inquiry phases: preparing and planning, performing and analyzing, constructing knowledge and modeling, communicating and management (Table I).

1. Change trends in aspects between stations

A closer observation of the relative frequency charts for the seven inquiry components (ICs) that were included in all the research stations (Fig. 2) reveals changes in the distribution of the relative frequencies of the perception of considerable level for each of the aspects, as the students advanced in the Research Physics program. The mean relative frequencies (mrf) are shown as brown horizontal segments. It is important to note that 8 additional ICs were

included for the Intermediate and Final stations, and the averaging was performed over all 15 ICs.

The Experience aspect chart for the Preparation station shows 6 of the 7 ICs ranging from 60% to 90% (“oral reporting” is a very low outlier) with “phrasing question/goals” and “data processing” at the top. The range was similar for the Intermediate station and narrowed to 79%–91% in the Final station. The mrf for the Experience aspect increased along the research stations from 63% to 76% and 79%. This indicates a widespread increasing perception of considerable Experience among the students (over all ICs). Regarding the position of the relative frequencies of the seven ICs with respect to the mrf, a general upward trend is visible with a close clustering above the mrf of 79% at the Final station. Five of the seven inquiry components have high relative frequencies (>60%), all above the mrf, throughout the research stations. However, “written reporting on the inquiry” has a relative frequency of around 60% for the first and second stations, which indicates that many students endorsed this inquiry component as one with which they perceived considerable Experience, yet for both these stations, the relative frequency is less than the mrf. Only in the Final station, the 90% votes of considerable Experience position this inquiry component above the mrf.

These findings are compatible with information in Appendix B (columns c–i), which shows that most of the students engaged in all seven ICs in the different

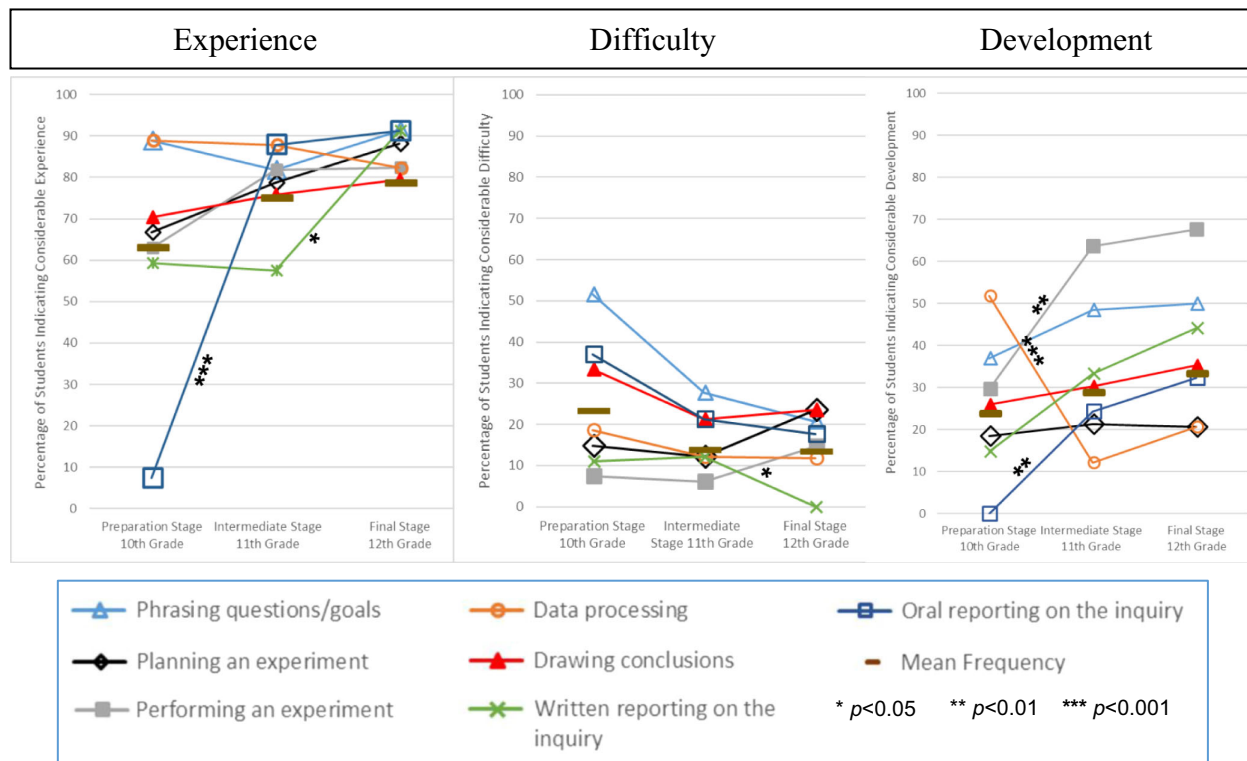


FIG. 2. Relative frequencies (%) and mean relative frequencies (%) of seven core inquiry components for Experience, Difficulty, and Development aspects at the three research stations.

program stages, especially toward the end of the stage, when the questionnaires were filled.

The Difficulty aspect chart for the Preparation station shows the relative frequencies for the 7 ICs on a wide range (8%–51%) evenly distributed around the mrf of 23%. The relative frequencies tend to decrease and their range narrows between the Preparation station and the Intermediate and Final stations. Three of the seven ICs remained above the mrf throughout the research stations: “phrasing questions or goals,” “drawing conclusions,” and “oral reporting on the inquiry.” The mrf decreases quite steeply between the Preparation and Intermediate stations and remains at a steady 12% in the Final station. This indicates a general low and decreasing perception of considerable Difficulty among the students regarding all ICs. This means students gradually found the inquiry components less challenging and felt more able to perform them.

The Development aspect chart for the Preparation station shows the relative frequencies for the 7 ICs on a wide range (0%–51%) evenly distributed around the mrf of 23%. The relative frequencies tend to increase consistently and their range remains similar between the Preparation station and the Intermediate and Final stations. Finally, the relative frequencies ranged between 20% and 68% around the mrf of 33%. The mrfs for the Development aspect were in the low-medium values (24%–32%) and increased somewhat as the program progressed. This indicates a moderately increasing perception of considerable Development regarding the ICs among the students. Of the 7 inquiry components, 3 have low to medium initial relative frequencies (25%–38%) and increase between the stations, remaining

above the mrf throughout the research stations: “phrasing questions or goals,” “performing an experiment” and “drawing conclusions,” with “performing an experiment” maintaining the top position for the Intermediate and Final stations. In contrast, “data processing” exhibits an unusual trajectory from the top relative frequency for the Preparation station to the lowest position at the Intermediate and Final stations.

2. Significant changes in relative frequencies between research stations

For each inquiry component and each research station, we used the frequencies of considerable level votes for each of the three aspects—Experience, Difficulty, and Development to run a chi-square test of independence, to determine whether the changes between stations were significant. Table III presents the inquiry components for which significant changes between stations were found in the frequency of considerable level votes for the Experience, Difficulty, or Development aspects. Note that each result refers to changes between two out of the three stations.

For the Experience aspect, significant changes were found between stations 1 and 2 and 1 and 3 for “oral reporting on the inquiry” (increase $p < 0.0001$). This change can be explained by the fact that while students had little if any experience of that inquiry component during the Preparation stage, presenting an oral report was a requirement toward the end of the Intermediate stage when the intermediate report was submitted. This requirement reemerged toward the end of the Final stage for the submission of the summative report, which required

TABLE III. Chi-square test of independence results: inquiry components with significant changes in relative frequencies (RF%) of considerable level votes between research stations for the Experience, Difficulty, or Development aspects (percentages rounded to the nearest integer).

Aspect	Inquiry component	Station 1 RF (%)	Station 2 RF (%)	Station 3 RF (%)	χ^2	p value
Experience	Planning an experiment	67		88	4.1748	0.041
	Oral reporting on the inquiry	7	88		38.5081	<0.0001
		7		91	42.5273	<0.0001
	Written reporting on the inquiry		58	91	9.9849	0.0016
Difficulty		59			8.6695	0.0032
	Phrasing questions or goals	52		21	6.5159	0.0107
	Written reporting on the inquiry		12	0	4.3829	0.0363
		11		0	3.9732	0.0462
Development	Performing an experiment	30	64		6.877	0.0087
		30		68	8.703	0.0032
	Data processing	52	12		11.1624	0.0008
		52		21	6.515	0.0107
	Oral reporting on the inquiry	0	24		7.5524	0.006
		0		32	10.65	0.001
	Written reporting on the inquiry					
		15		44	6.025	0.014

reflection upon the entire inquiry process and response to feedback from peers and teacher-mentor evaluators. This trend emerges from observations and student products as demonstrated in Appendix B (column h). The fact that the questionnaires were filled toward the end of each program stage probably contributed to the student's awareness of the extent of their recent experience.

A significant increase in the Experience aspect was found for “written reporting on the inquiry,” between stations 2 and 3 and 1 and 3. The increase between stations 2 and 3 ($p = 0.0016$) and 1 and 3 ($p = 0.0032$) can be explained by the fact that with the progress in the inquiry project, the students experienced this component more intensively. They had to be more careful about documenting the inquiry and they wrote laboratory reports independently. All this led to the compilation of the summative report, which formed the basis for the internal and external evaluations.

A moderately significant increase ($p = 0.041$) in the Experience aspect of “planning an experiment” was found between stations 1 and 3. This can be easily explained by the program structure that focused on relatively structured experiments in the 10th grade, in contrast to the open-inquiry during the long-term inquiry project. This trend emerges from observations and student products as demonstrated in Appendix B (column d).

For the Difficulty aspect, significant decreases were found between stations 1 and 3 ($p = 0.0462$) and 2 and 3 for “written reporting on the inquiry” ($p = 0.0363$) and between stations 1 and 3 ($p = 0.0107$) for “phrasing questions or goals.” The decrease in the Difficulty aspect of “written reporting on the inquiry” can be explained by the program structure that provided scaffolding during the Preparation and Intermediate stages via instructions for the organization and written representation of their data, as well as tools that prepared students for composing the summative report and the final presentation. An additional factor that is mentioned in the students' comments is that the support of the teacher-mentor was sufficient to deal with these difficulties and allowed them to progress. The decrease in the Difficulty aspect of “phrasing questions or goals” can be explained by the program structure which included frequent practice of formulating inquiry questions and inquiry goals, as well as the scaffolding of that component by the teacher-mentors.

For the Development aspect, significant changes were found for “performing an experiment”: an increase between stations 1 and 2 ($p = 0.0087$) and stations 1 and 3 ($p = 0.0032$). The increase in the Development aspect of “performing an experiment” can be explained by the fact that in the early stages of the inquiry project, the students carried out initial experiments to understand the researched phenomenon. In the later stages, the students engaged in more advanced and complex experiments and dealt with the dynamics of experiments, such as changing the experiment

system to accommodate new directions of investigation, constant improvement of the experiment system, and repeating an experiment to obtain more precise measurements. The students reported that they developed their determination, perseverance, and creativity in order to provide solutions to problems that surfaced during the experiment. In the advanced stages of the inquiry, the students carried out more experiments independently, accompanied and supported by the teacher-mentors. Observations showed that the students displayed more independence and initiative in the performance of experiments, which may have increased their feeling of ownership over the inquiry and sense of development in performing experiments.

The decrease in the Development aspect of “data processing” between stations 1 and 2 ($p = 0.0008$) and stations 1 and 3 ($p = 0.0107$) can be explained by observation data showing that the methods that were first employed during the Preparation stage continued to be used in the more advanced stages. These methods were similar to those used in the school physics laboratory (e.g., comparison to the theoretical value and calculating the relative error; noting possible error sources without calculating the measurement uncertainty). The results indicate that students may have felt that they had achieved expertise in “data processing” in the Preparation stage and did not perceive further development in the later stages.

The increase in the Development aspect of “oral presentation of an inquiry report” between stations 1 and 2 ($p = 0.006$) and stations 1 and 3 ($p = 0.001$) can be explained by the fact that this component was experienced mainly in the advanced stages of the program. The students reported that these experiences had led to an improvement in their ability to present in front of an audience, an increase in their sense of efficacy, and a reduction of the stress and anxiety in presenting orally. In addition, the feedback they received enabled them to critique their work and improve their performance. The increase in the Development aspect of “written reporting on the inquiry” between stations 1 and 3 ($p = 0.014$) can be explained by observation data showing intensive practice and effective scaffolding.

The trends of change were tracked for each of the aspects regarding seven core inquiry components that were included in all three research stations. The picture that emerges shows a general increase in the percentage of students who perceived considerable Experience and Development and a decrease in the perception of considerable Difficulty. Since these 7 inquiry components represent the 4 central inquiry phases, and since the mean relative frequencies (depending on all 15 components) follow the same trend, the results may reflect a general trend in students' perceptions of considerable level toward the three aspects, for most of the inquiry components. We offered some explanations for the trends regarding specific inquiry components based on the Research Physics program structure.

B. Research question 2

Research question 2: How was students' perception of considerable Development related to their perceived considerable Experience and Difficulty with respect to a set of inquiry components along the research physics sequence?

1. Additional data analysis—Integrated rating of aspects

For each of the 15 final inquiry components, integrated ratings of perceived considerable Experience, Difficulty, and Development across all 3 research stations were created. The integrated ratings were intended for seeking relationships between perceived aspects of inquiry components, spanning the entire research period.

The general rule we adopted for defining the integrated rating for an aspect of a given inquiry component was as follows: if the relative frequency of the aspect was equal to or exceeded the mean relative frequency for at least two of the three stations, the rating for that aspect would be High. Otherwise, it would be Low. Appendix G shows examples of High and Low ratings for the aspects of the seven inquiry components that were included in all three research stations.

2. Groups of inquiry components

In this part of the research, we intended to test the hypothesis that High perceived Experience and High perceived Difficulty, related to inquiry components, are associated with High perceived Development, and vice versa. Four groups of inquiry components were found, which differ in the relationship between the integrated ratings of students' perceptions of considerable Development, Experience, and Difficulty during the entire Research Physics program. Table IV specifies the ratings of

perceived considerable Experience, Difficulty, and Development for each of the four groups. Note that three of the inquiry components are marked with asterisks, as they conform to the group pattern in two of the three aspect ratings, particularly in the Development aspect.

Inquiry components rated High can be considered prominent inquiry components in students' perception of each aspect. According to Table IV and Appendix G, the prominent inquiry components are as follows: Experience aspect—groups 1, 2, and 4; Difficulty aspect—Group 1 and “oral reporting on the inquiry” in group 4; Development aspect—groups 1 and 2. Additional information about the rating of inquiry components is described in the following findings for each of the groups.

The findings indicate that for groups 1 and 3 (consisting of 7 of the 15 inquiry components), the research hypothesis about the relationship between the degree of perceived Experience and degree of perceived Difficulty along the program and the degree of perceived Development in these components was validated. However, for the inquiry components in groups 2 and 4, the results do not match the research hypothesis. Following is a detailed description of the relevant graphs for each group.

Group 1. *High perceived Development is associated with High perceived Experience and Difficulty:*

Figure 3 presents the percentage of students who indicated considerable Experience/Difficulty/Development (respectively) in the performance of the inquiry components: “phrasing questions or goals”, “drawing conclusions,” and “building content knowledge,” and exceeded the mean relative frequency at least at two research stations.

These results are in agreement with the intended structure of the program for the Experience aspect and with the observation data as demonstrated in Appendix B (columns

TABLE IV. Inquiry component groups by High or Low ratings for the Experience, Difficulty, and Development aspects. *Inquiry components that conform to the group pattern in two of the three aspect ratings.

Group	Inquiry components	Experience	Difficulty	Development
1	Phrasing questions or goals Drawing conclusions Building content knowledge	High	High	High
2	Performing an experiment Self-regulation Teamwork with the partner Written reporting on the inquiry* Choosing a topic or investigation directions*	High	Low	High
3	Locating information sources Using technological aids and a computerized laboratory Building a theoretical model Teamwork with the other peers in the broad group	Low	Low	Low
4	Planning an experiment Data processing Oral reporting on the inquiry*	High	Low	Low

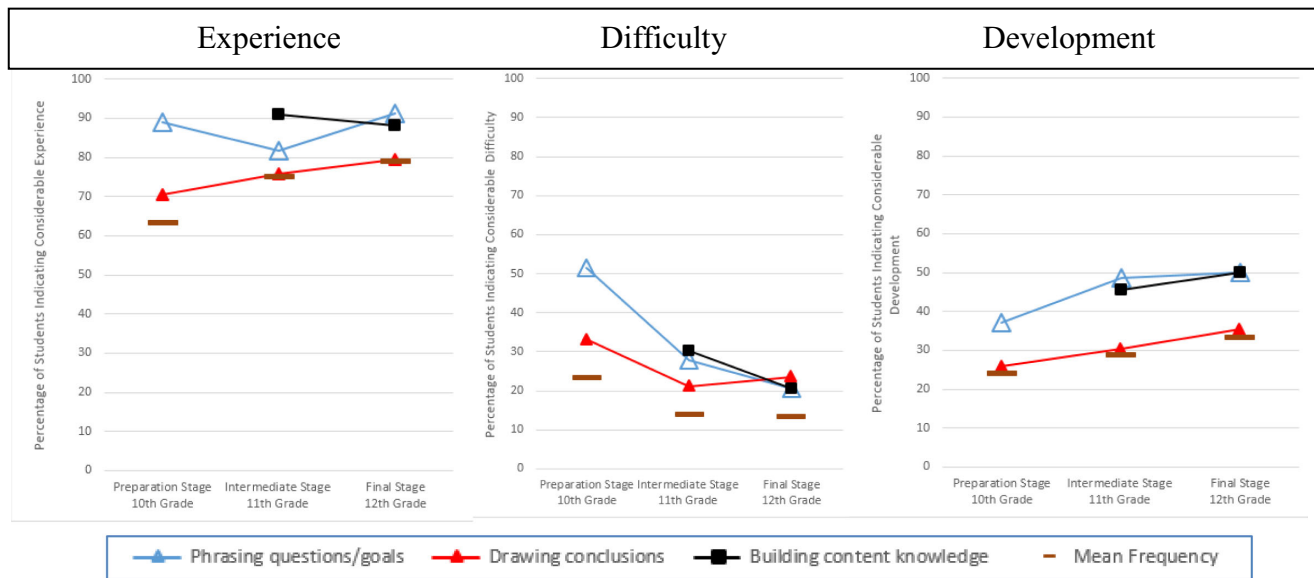


FIG. 3. Group 1 inquiry components—Relative frequencies (%) and mean relative frequency (%) of student votes of considerable Experience/Difficulty/Development at the three research stations.

c, g, j). The program required the students to refine and focus the inquiry questions throughout the 3-year sequence and repeatedly address gaps between experimental findings and the theory, through independent or mentor-mediated learning of complex theoretical material.

In addition, the perceived Difficulty of the three inquiry components decreased throughout the program sequence but remained above the mean relative frequency. Coping with these components was perceived by the students as especially challenging. In the qualitative analysis of students' answers to the open questionnaire items, some of the difficulties that the students described for these inquiry components are the same aspects for which the students noted they had developed. Following is some evidence quoted from student comments:

"Phrasing the inquiry question—this was especially hard for us as a team in the beginning, but with time we phrased a large number of questions. We learned that it is necessary to construct the question: How a certain variable influences another variable? and we improved in this skill, which will follow us next year" (station 2).

"I found the situation of independent learning during the inquiry work to be difficult. Although there was support from the teacher-mentor, it was hard for me to understand the theory related to the phenomenon and to cope with building knowledge independently, since I did not have previous knowledge at all and I needed to learn a lot by myself, during the experiments. However, in spite of this difficulty I grew. This situation caused me to know how to learn and how to build knowledge independently, which I had not done in the past" (station 3).

"There was a difficulty in the comparison between theory and experiment since there is a large gap between the

theoretical world and the real world, and therefore we needed to think and to critique what we did and to investigate further to reach more correct conclusions and this developed us in the skill of drawing conclusions ..." (station 3).

In conclusion, for the inquiry components of group 1, the findings are in keeping with the research hypothesis that High perceived Development is associated with High perceived Experience and Difficulty.

Group 2. *High perceived Development is associated with High perceived Experience, while the perceived Difficulty is Low:*

Figure 4 presents the percentage of students who indicated considerable Experience, Difficulty, or Development (respectively) related to the inquiry components: "performing an experiment," "self-regulation," "teamwork with the partner," "written reporting on the inquiry" and "choosing a topic." "Performing an experiment" and "written reporting on the inquiry" were measured at all three research stations, while the other three were only measured at the second and third research stations. The relative frequencies for these inquiry components were usually above the mean relative frequency for the Experience and Development aspects, yet below the mean relative frequency for the Difficulty aspect.

We shall start with the findings for the first three inquiry components. The High integrated rating of perceived Experience for "performing an experiment" matches the observations and the Research Physics program structure (Appendix B, column e). Students were called upon to perform increasingly complex experiments in the transition between the Preparation to the Intermediate and Final stages. Working on their chosen inquiry projects students started with simple exploratory experiments and

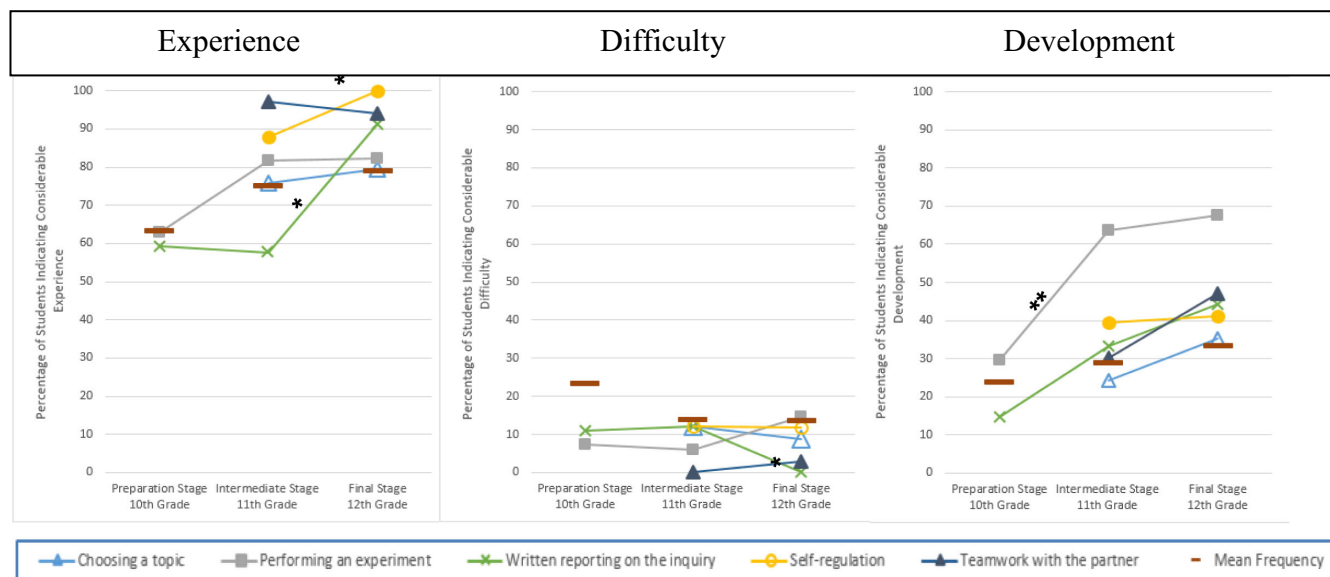


FIG. 4. Group 2 inquiry components—Relative frequencies (%) and mean relative frequency (%) of student votes of considerable Experience/Difficulty/Development at the three research stations.

progressed to building a steadily more complex and sophisticated experimental system and to performing more precise measurements. High perceived Experience of “self-regulation” can be associated with the requirements of planning and organizing the inquiry, meeting deadlines, making informed decisions in situations of uncertainty, and coping with frustration. High perceived Experience of “teamwork with the partner” can be associated with the division of tasks between team members to achieve greater efficiency, cooperative learning with the partner, and mutual commitment and brainstorming for solving problems.

The perceived Difficulty was Low for the first three inquiry components. This can be associated with the support received from the laboratory technicians, who provided equipment and technical assistance, and from the teacher-mentors through the follow-up and formative assessment of planning and progress in the inquiry.

The perceived Development was High for the first three inquiry components. Students ascribed their success in managing the inquiry to their seriousness, responsibility, dedication, and creativity as individuals and as research teams. It would seem that the extensive experience in these components led to an improvement of the quality of the experiment system and the development of practices of self-regulation of the inquiry work and interpersonal abilities in teamwork. The following student comments indicate the contribution of the intense experience to the perceived Development.

“Performing the experiment—as we built the system more times we improved in the accuracy of the measurements and in the time efficiency” (station 2).

“I improved in self-management of the process. Before the project I was not accustomed to plan what and how to

research and how to conduct or organize the research work completely by myself and to be responsible for the advancement of the project, but after the practice during the inquiry work this became easier and more simple” (station 2).

“Teamwork—my team partner and I had to work continuously and consistently, which was a little complicated for us at first, but with time and due to working together a lot, the coordination between us improved. We divided the work between us and we understood one another on the highest level” (station 2).

As for “written reporting on the inquiry” and “choosing a topic” the picture is a little different. The integrated rating for the Experience aspect of “written reporting on the inquiry” only exceeded the mean relative frequency at the Final research station. This finding does not match the Research Physics program structure (Appendix B, column i), which required written reports in all the program stages. In the Final stage, the requirements intensified to include reports in different formats: an inquiry journal and a summative report. The integrated rating for the Experience aspect of “choosing a topic” is High for the Intermediate and Final research stations which is compatible with observations and the Research Physics program structure (Appendix B, column a). As the inquiry projects proceeded, it became necessary to re-think the investigation directions and to decide on preferred foci.

The perceived Difficulty rating is Low for both discussed inquiry components. However, some students did describe difficulties in their ability to persevere in documenting the inquiry and in summarizing the main points, as well as coping with changes in investigation directions and selecting the most productive topic and focusing on it.

The perceived Development rating is High for “written reporting on the inquiry,” and only exceeds the mean relative frequency for “choosing a topic” at the Final research station. These findings can be related to the support and direction of the teacher-mentors, who helped students differentiate between important and less important information, and produce better organized, more concise, and clearer writing. The following student comments indicate the contribution of the intense experiencing to the perceived Development.

“I developed in written reporting and documenting of the inquiry work. For two years in the program I dealt a lot with creating a research journal and with writing of the detailed laboratory reports...Also in management and summarization of the research activities in an orderly and consistent manner. This is something in which I would not have improved if I had not experienced it a lot in a program” (station 2).

“Choosing a topic—we changed the topic of the project since during the investigation of the initial topic we encountered a strange phenomenon that we did not expect and that interested us...It made me realize that inquiry is dynamic and there is no need to panic about it, but to deal with being flexible with the investigation and in the end knowing how to choose and focus on the topic you have chosen” (station 3).

In conclusion, for group 2 inquiry components, students’ reports reflect High perceived Experience, while the

students were not greatly challenged (Low perceived Difficulty) and still achieved High perceived Development in their ability to perform these components. These findings are partially in keeping with the research hypothesis. It would seem that for these components, the extensive perceived Experience was sufficient to generate High perceived Development.

Group 3. *Low perceived Development is associated with Low perceived Experience, and Low perceived Difficulty:*

Figure 5 presents the percentage of students who indicated considerable Experience/Difficulty/Development (respectively) regarding the inquiry components: “locating information sources,” “using technological aids and a computerized laboratory,” “building a theoretical model,” and “teamwork with the other peers in the broad group,” which were only included in the questionnaires of the second and third research stations. For all three aspects, all group 3 relative frequencies were not above the mean relative frequency, at both research stations.

Observation data reflect evidence that students engaged in group 3 inquiry components in a limited manner. They were less required to locate information sources relevant to the researched topic along the program and emphasis was not placed on “building a theoretical model” using computational modeling as demonstrated in Appendix B (columns b and k). In addition, only particular inquiry teams used technological aids and a computerized laboratory. Students only had extensive experience in the component of teamwork with the other peers in the broad group during the Intermediate stage, within the framework of presentation to peers, and peer assessment. The few students who

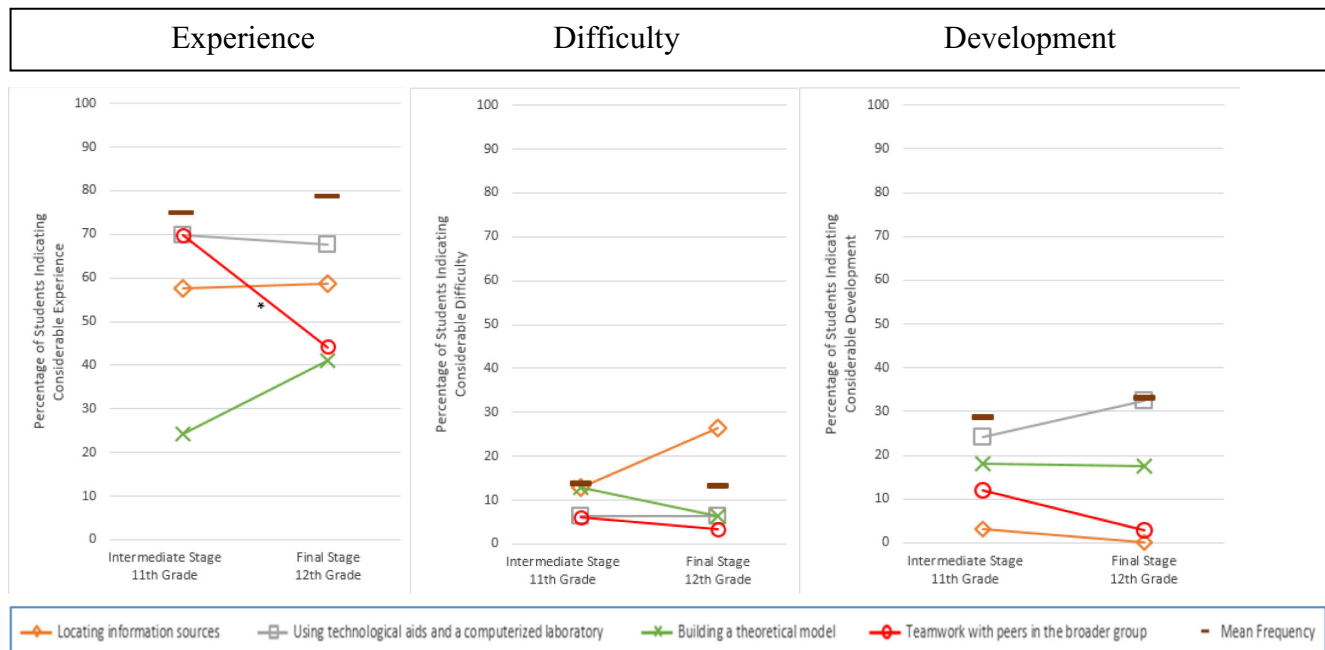


FIG. 5. Group 3 inquiry components—Relative frequencies (%) and mean relative frequency (%) of student votes of considerable Experience/Difficulty/Development at the three research stations.

did report considerable Development in this component indicated that the importance of “teamwork with peers in the broad group” and particularly performing peer assessment (which provided them with suggestions for improvement), gave them satisfaction and confidence in their work and their presentation, and exposed them to their peers’ inquiry projects.

Qualitative analysis of students’ answers to the open questions indicated that only at the Final stage of the inquiry project did students encounter considerable difficulty in identifying sources relevant to the researched phenomenon. Their difficulties stemmed from several reasons: the uniqueness of the phenomenon, finding few sources dealing with the phenomenon, or a lack of knowledge and experience in finding quality information sources. Observation-based evidence indicates that most of the teacher-mentors did not provide the required support for these issues, and the students settled for the resources they had found or those the teacher-mentors provided.

In conclusion, Group 3 inquiry components represent Low perceived Development associated with Low perceived Experience and Difficulty, which is in agreement with the basic research hypothesis.

Group 4. *Low perceived Development associated with High perceived Experience and usually Low perceived Difficulty:*

Figure 6 presents the percentages of students who indicated considerable Experience/Difficulty/Development (respectively) regarding the inquiry components: “planning an experiment,” “data processing,” and “oral reporting on the inquiry” at the three research stations. The integrated ratings for the perceived Experience and Development were High and Low, respectively. The integrated rating for the

Difficulty aspect was Low, except for “oral reporting on the inquiry.”

The High perceived Experience can be related to the Research Physics program which required repeated engagement in planning experiments, data processing, and oral reporting (Appendix B, columns d, f, and h). Planning an experiment involved designing experiments, defining the required equipment as well as defining and isolating variables. The Preparation stage exposed students to a variety of data-processing technical tools that were new to 10th-grade physics learners. The students continued implementing these tools for their inquiry projects in the 11th and 12th grades. Oral reporting was required toward the end of the Intermediate and Final stages of the Research Physics program. Students presented their inquiry methods and results in front of teacher-mentor and peers.

The perceived considerable Difficulty ratings for group 4 inquiry components are inconsistent: Low for “planning an experiment” and “data processing” and High for “oral reporting on the inquiry.” The following student comments confirm that “oral reporting on the inquiry” remained a source of difficulty throughout the program:

“Presenting orally—it was hard for me to stand in front of people who are looking at me and to talk. I did not really succeed in coping. I do not really remember what happened there aside from the anxiety I felt” (station 2).

The decrease in perceived Difficulty for this component at the Final station can be explained by repeated practice and group strategies students adopted to overcome their anxiety:

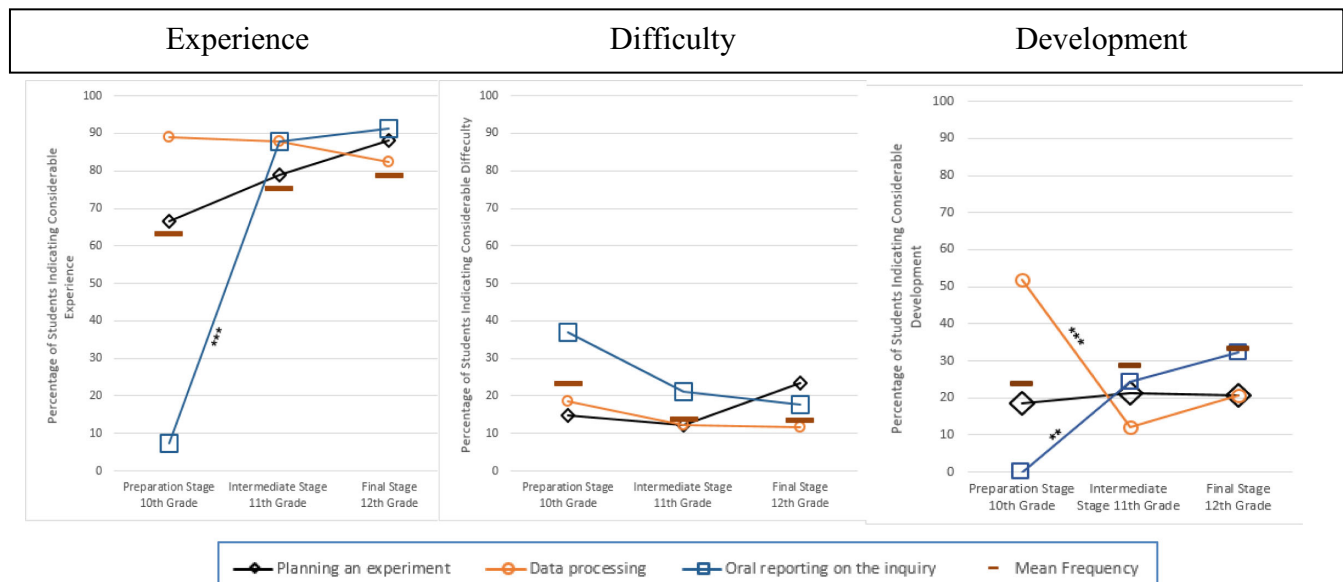


FIG. 6. Group 4 inquiry components—Relative frequencies (%) and mean relative frequency (%) of student votes of considerable Experience/Difficulty/Development at the three research stations.

“Oral presenting in front of others, in my opinion, this really developed in me because I had a real fear and anxiety of speaking before an audience. From year to year, the pressure and anxiety have decreased, and every additional presentation improved my feeling of confidence and ability of speaking in front of an audience” (station 3).

The perceived Development is Low for all group 4 inquiry components, which may be related to the insufficient scaffolding students received. The observation data indicated that the program did not explicitly provide tools (e.g., templates) for planning experiments nor for preparing and coping with the emotional stress involved in facing an audience. Feedback on planning experiments and oral presentations depended on each teacher-mentor’s decisions. Some problematized the planning task, while others simply proposed planning solutions without allowing the students to cope independently. Students were not given opportunities to improve their oral presentations following the feedback they received. Regarding data processing, the program did not require the use of advanced statistical analysis tools, beyond the standard tools that were introduced at the Preparation stage. Evidence from student comments indicates that a minority of students did perceive considerable Development in group 4 inquiry components, and this trend increased toward the Final stage of the Research Physics program. However, the majority of the class did not share this perception.

In conclusion, Group 4 inquiry components represent Low perceived Development associated with High perceived Experience and usually Low perceived Difficulty, which conflicts with the basic research hypothesis.

VII. SUMMARY AND DISCUSSION

The Research Physics program was designed as part of a national effort to respond to recent and past calls to involve science learners in open-inquiry. The program offered an environment in which the main constraints on long-term open-inquiry for high school physics students, namely time, teaching force, and equipment, were significantly reduced.

The Research Physics program recruited motivated 10th-grade physics students from several schools to become members of a regional class that met for biweekly afternoon sessions in the well-equipped laboratories of a science education institution and engaged in a range of inquiry activities under the supervision and guidance of expert teachers. The teacher-mentors were physics teachers with varied backgrounds, teaching experience, and perceptions of their role as inquiry mentors. Most of them performed inquiry mentoring as part of their training to become accredited Research Physics mentors.

The current research summarizes quantitative and qualitative data gathered by the first author over a period of

3 years (2016–2019), as she researched the experiences and perceptions of 34 high school students, who coped with the demands of open-inquiry in the unique Research Physics program. The main data resources were questionnaires the students filled out toward the end of three stages of the program—Preparation, Intermediate, and Final, in which they reported their perceived levels of Experience, Difficulty, and Development regarding a set of inquiry components. Additional information was collected by observing student teams and their teacher-mentors as they implemented the inquiry practices required by the structure of the Research Physics program (Appendix B).

The data analysis addressed two research questions regarding the perceived considerable Experience, Difficulty, and Development as related to the set of inquiry components. The first research question dealt with trends and changes along the three stages, while the second research question dealt with the relationship between the three aspects throughout the program. The research hypothesis was that a high degree of perceived Development would be associated with high degrees of perceived Experience and Difficulty. It is also reasonable to assume that student perceptions were shaped by the Research Physics program structure (Appendix B) and the actual implementation of the intended program by individual students and their teacher-mentors.

The findings regarding the first research question focused on seven representative inquiry components. The chi-square test of independence showed significant changes regarding relative frequencies between stations for most of the seven inquiry components. “Oral and written reporting on the inquiry” tended to increase significantly in the aspects of Experience and Development toward the Final research station. A significant increase between the Preparation and Final stations was noted for the Experience aspect of “planning an experiment” and the Development aspect of “performing an experiment.” These results are consistent with the program structure as well as the scaffolding that enabled students to respond to the increasing challenges. A significant decrease in the perceived Difficulty for “phrasing questions or goals” and “written reporting on the inquiry” toward the Final station may be related to increased skills and focused teacher-mentor support.

The findings regarding the perceived Development indicate that as the program progressed and the students were required to deal with the complexities of open-inquiry, a certain percentage achieved a perception of considerable Development for each of the seven inquiry components. Notably, almost 70% perceived considerable Development for “performing an experiment”—an activity with which they had been involved since the beginning of the program, while only about 20% perceived considerable Development for “planning an experiment.” This seeming contradiction is difficult to explain, particularly in view of the fact that

considerable Experience was reported for the “planning an experiment” inquiry component by around 90% of the students. Observation data indicated that some teacher-mentors tended to play an overprotective role in planning experiments, thus trying to ensure their project team’s success. Further discussion concerning this and other inquiry components is provided in the following section.

The findings regarding the second research question yielded four groups of inquiry components, each of which presents a different relationship between the integrated ratings of perceived Experience, Difficulty, and Development. The guiding research hypothesis was that a High perceived Development for an inquiry component would be associated with High perceived Experience and Difficulty, and vice versa. Group 1 (“phrasing questions or goals,” “drawing conclusions,” and “building content knowledge”) and Group 3 (“locating information sources,” “using technological aids and a computerized laboratory,” “building a theoretical model,” and “teamwork with the other peers in the broad group”) upheld the research hypothesis, while Group 2 (“choosing a topic,” “performing an experiment,” “self-regulation,” “teamwork with the partner,” and “written reporting on the inquiry”) and Group 4 (“planning an experiment,” “processing data,” and “oral reporting on the inquiry”) did not exhibit the expected relationship. These findings raise two queries: What enabled High perceived Development despite Low perceived Difficulty in Group 2? What prevented High perceived Development despite the High perceived Experience in Group 4? These seeming anomalies require a deeper understanding of the Research Physics program ecology.

Lab technicians and teacher-mentors provided comprehensive scaffolding for the inquiry components of Group 1 and Group 2. The observations indicate that there was continuous and frequent attention to the interaction between the teacher-mentor and students. With time,

teacher-mentors gradually reduced the students’ reliance on them and students’ ability to perform these components grew, thus overcoming the challenges of performing these inquiry components and decreasing the perception of difficulty. We may assume that Low perceived Difficulty is related to the feeling of self-efficacy in providing answers to problems that arose along the way and the sense of ownership and enjoyment derived from it [75].

Group 4 inquiry components “planning an experiment,” “data processing,” and “oral reporting on the inquiry” were core inquiry components, which formed routine practices of the activities students engaged in throughout the Research Physics program, which explains the High perceived Experience. These are also traditional lab practices physics students experience at school to some extent. Table V contrasts the school lab culture and the Research Physics culture for the two inquiry components and indicates the need for boundary crossing between the cultures. The Research Physics program intended to advance students’ knowledge and skills beyond the high school norms, thus necessitating boundary crossing [32] (p. 2).

In the 2016–2019 period, the intended Research Physics program was mediated by trainee teacher-mentors, so the level of sophistication students met depended on the teacher-mentors’ own expertise and on their role perception [33,76]. The Research Physics program did not provide templates guiding the feedback for planning an experiment, processing data, and oral reporting on the inquiry. The wide spectrum of expertise and role perception among the teacher-mentors coupled with the natural variation in student-team ability and motivation resulted in a complicated pattern of perceived Difficulty and Development. For students to gain a perception of considerable Development, the level of sophistication and the level of scaffolding provided by teacher-mentors should have been sufficient to help student teams bridge the gap

TABLE V. Comparing school lab and research Physics program cultures for sample inquiry components.

Inquiry component	School lab culture	Research Physics program culture
Planning an experiment	Students usually perform short-duration, traditional labs guided by a detailed instruction sheet [11]. Thus, planning is not required nor practiced. The experiment is intended to confirm the theory studied in class and the expected lab outcomes are known ahead of time.	Student teams inquire into different topics for an extended duration of 18 months. The expected inquiry outcomes are not known and the inquiry path needs to be designed which includes planning experiments and identifying and controlling variables. Students are given considerable autonomy and responsibility in the inquiry process.
Oral reporting on the inquiry	Is performed (if at all) only after the completion of the lab experiment, for the purpose of summative assessment.	Teams participated in several oral presentations of interim results before peers and teacher-mentors. These served as formative assessment, sources of feedback, and guidance toward evaluating and improving the inquiry process.

between the school culture and the Research Physics program culture. Few of the trainee teacher-mentors were able or willing to set high-level goals and scaffold the required student learning process to the extent the students felt they had achieved control of the expert levels of “planning an experiment,” “processing data,” and “oral reporting on the inquiry.” Thus, many teacher-mentors either restricted the challenge students experienced by keeping the goals close to the school level or set their teams’ ambitious goals while providing insufficient support. Both combinations would be counterproductive to creating a sense of considerable Development.

The findings also indicate possible weaknesses in the design or implementation of the Research Physics program. The findings indicate that the students did not perceive a considerable level of Development for all the inquiry components. This lack of perceived Development that is expected to be associated with perceived considerable Experience can be attributed to insufficient scaffolding either by the structure of the Research Physics program or by the functioning of the teacher-mentors. The findings indicate the necessity to provide support that enables students to handle the requirements and practices, which are more complex than those they can tackle by themselves.

Hence, it can be understood, that in performing inquiry components, it is not possible to rely solely on the extensive experience provided by the learning environment that focuses on inquiry, and it becomes clear that some of the inquiry components do not develop spontaneously with experience for most of the students but that appropriate scaffolding should be provided.

The above analysis has implications for designing a program that engages students in long-term inquiry and implications concerning the required instructional support.

Helping students develop required inquiry practices and abilities for resolving problems, involves enabling students to carry out nontrivial tasks and providing opportunities to formulate problems, propose problem-solving methods, overcome obstacles during the search for a solution, and critically examine the problem-solving results. At the same time, it is necessary to provide scaffolding by structuring, which guides the process of inquiry work, for example, breaking down complex tasks into subtasks that can direct students toward necessary actions in the process and for focusing their resources and learning, and helping structure and organize the problem-solving task [35]. To help students internalize the nature of inquiry and its components, it is necessary to expose them to dynamic changes that occur in the inquiry process, to set up objectives, to gradually elevate the standards required in the performance of inquiry components, and to adjust the intervention and support of the teacher-mentors helping the student attain the required objectives.

As teacher-mentors gradually reduce their support, increase the students’ freedom, empower the students,

and direct them to continue independently, they enable the students to cultivate their self-autonomy and solve problems independently [58]. To achieve this, teacher-mentors need to apply problematizing steps such as posing guiding questions, directing the students’ attention to actions of which they were not aware, and providing oral and written formative assessment and feedback for the students’ work. This will provide students with information about their learning and enable them to deploy corrective strategies as necessary, as well as thinking about the following steps in the investigation and following up the learning process they underwent [77]. This scaffolding can help students cope with the challenges they face during the inquiry project, support the students’ learning, and shape their performance and understanding of the inquiry.

The results of the current study can be useful in the search for effective teaching methods to promote inquiry learning in science teaching in general and in learning to become a high school physics inquirer, in particular.

The findings of the current study can serve to encourage education systems to promote initiatives and support learning environments that offer students opportunities to experience long-term meaningful science inquiry. This has the potential to lead to the integration of inquiry into science learning and make inquiry a main learning component, thus becoming a driving force for achieving science education goals [2,6].

VIII. RESEARCH LIMITATIONS

The current research followed the unfolding story of a group of 34 high school physics students of varied backgrounds learning to perform open-inquiry, for a prolonged, 3-year period during which the students underwent physical and mental maturation. A design-based research approach was employed [65], which indicates a “field experiment” in a naturalistic setting. Research of this type can boast of high ecological validity but naturally is prone to criticism with respect to the control of variables and external validity. One or more of the following causes might impact the external validity of the current study and limit its implementation scope and generalization of its conclusions to wider populations: the unique environment of the Research Physics program, the small sample size, the variation in the functionality of the teacher-mentors, and the strong reliance on data based on student self-report.

The current research was framed within the Research Physics program which can be considered a particular case study of environments intended to facilitate the engagement of high school physics students with long-term open-inquiry. The variation among the students and teacher-mentors is natural in educational reality and assures the ecological validity of the research. The program structure itself was identical for all participants and was designed to start by acquainting 10th-grade students lacking inquiry experience with physics inquiry. The teacher-mentors with

whom the students worked on their inquiry projects in years 11 and 12 did indeed present a varied group of individuals in terms of their physics knowledge background and expertise regarding the inquiry topic, their perception of physics inquiry, and their perceived role as inquiry mentors. The teacher's personality, background, and views were likely to impact the students' learning experience during the inquiry [48]. In addition, the students' learning and perception of inquiry may have been influenced by other agents such as members of the program staff who were involved in carrying out the Research Physics program. However, a fact that could mitigate the effects of the personal variety among the teacher-mentors is that the Research Physics program coordinated their behavior. Most of the teacher-mentors performed the inquiry mentoring as part of their training to become accredited inquiry mentors. As trainees, they belonged to an "inquiry mentor community" and received uniform instructions concerning their recommended interaction with the student teams and ways of supporting them.

The main research tools employed by the current study were self-report questionnaires administered at three stations, toward the end of each of the 3 years. This method of data collection is clearly subjective, and the ability to draw valid conclusions from such data depends on the reliability of student responses on each questionnaire. While there is little suspicion that the students deliberately misrepresented their perceptions, the validity issue is about students' interpretation of the listed inquiry components and the aspects of Experience, Difficulty, and Development. These issues have been addressed (Secs. [VD 1](#) and [VE 3](#)) to reduce the possible threat of this limitation.

Cross-checking the quantitative results against the qualitative data analysis served to verify the group profile of students' perceptions. In particular, observation-based information helped address the issue that questionnaires were filled at the end of each of the program stages and student ranking might be affected by recent events rather than based on their experiences throughout the year. For the most part students' questionnaire reports were in agreement with the qualitative data. The qualitative data served to illustrate and clarify the results of the quantitative data analysis and thus added validity to the research conclusions.

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APPENDIX A: LIST OF STUDENT PROJECTS IN THE RESEARCH PHYSICS PROGRAM

Table VI presents the list of student inquiry projects in the research physics program.

TABLE VI. List of student inquiry projects.

Project name
Magnus force in a wind tunnel
Water bubbles in oil
Magnus force—flying cups
Optics—from rays to waves—rainbow
Incandescent light bulb as a light source and its spectrum
On waves and strings—characterization of oscillations in the guitar string and the sound obtained from it
Investigation of springs and Slinky
Movement of Brownian particles interacting with a glass surface
Wilberforce pendulum
Polarization
The dispersion ratio of water waves in a tank
Sound waves—the limits of sounds
Spread of a Kalium Permanganate tincture stain in water
Coupled carts
Parametric resonance in pendulums
Electron motion in electromagnetic fields
Vibrations in a string

APPENDIX B: MAPPING INQUIRY COMPONENTS TO ACTIVITIES OF THE RESEARCH PHYSICS PROGRAM

Table VII presents for each activity the inquiry components that the students engaged in, based on observation of the sessions and students' products. Note that the number of sessions devoted to each activity should be taken as a multiplier to assess the level of engagement of students with inquiry components.

TABLE VII. Mapping inquiry components to activities of the Preparation, Intermediate, and Final stages of the Research Physics program (✓ = most of the students, some = some of the students, ... = none).

Inquiry component	a	b	c	d	e	f	g	h	i	j	k
Activity	Choosing a topic or investigation directions	Locating data sources	Phrasing questions/ goals	Planning an experiment	Performing an experiment	Data processing	Drawing conclusions	Oral reporting	Written report	Building content knowledge	Building a theoretical model
Preparation stage—10th grade											
1: Trolley uniform motion (1 session)	...	...	...	...	✓	Some	...	Some	✓	...	...
2: Falling paper cup (1 session)	...	...	...	...	✓	✓	Some	Some	✓	...	...
3: Atwood's machine (2 sessions)	...	...	✓	...	✓	✓	✓	Some	✓	Some	Some
4: Roemer experiment (2 sessions)	...	Some	...	...	✓	✓	Some	...	✓	✓	...
5: Investigation of springs (2 sessions)	✓	Some	✓	✓	✓	✓	✓	✓	✓	Some	Some
6: Mini-project (4 sessions)	✓	Some	✓	✓	✓	✓	✓	✓	✓	✓	Some
Intermediate stage—11th grade											
1: Computational modeling (Structured activities, 7 sessions)	...	...	...	...	...	✓	✓	...	✓	Some	✓
2: Summative task in computational modeling (2 sessions)	...	...	✓	...	...	✓	✓	...	✓	Some	✓
3: Work on the project until submitting an intent document (12 sessions)	✓	Some	Some	Some	✓	Some	Some	...	✓	Some	Some
4: Work on the project until submitting a midterm report (12 sessions)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Some
Final stage—12th grade											
1: Work on the project until submitting an intent document (11 sessions)	✓	Some	✓	✓	✓	✓	✓	...	✓	✓	Some
2: Work on the project until submitting a summary report (16 sessions)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

APPENDIX C: RESEARCH QUESTIONNAIRE (PARTS B AND C)

Part B: The following table presents a list of different possible components in the process of work on the inquiry project.

- To what degree did you experience performing these components?
- To what degree did you experience difficulty in coping with these components?

Please note that in every row it is necessary to indicate two responses: regarding the level of experience and the level of difficulty.

TABLE VIII. Questionnaire part B heading format. To save space the list of inquiry components is shown beneath the table heading.

	0 No experience at all	1 A certain experience	2 Considerable experience	0 No difficulty at all	1 A certain difficulty	2 Considerable difficulty
Inquiry components						

List of the inquiry components that appeared in the left column of Table VIII:

- | | |
|---|---|
| 1. Choosing the topic for the project | 15. Examining actions performed during the project for the choice of new directions |
| 2. Formulating questions about the physical phenomena the project addressed | 16. Documenting the inquiry process |
| 3. Focusing the inquiry question | 17. Organizing the work |
| 4. Planning the work | 18. Meeting the time schedule |
| 5. Planning an experiment system to provide an answer to the inquiry question | 19. Writing a presentation for reporting on the project |
| 6. Isolating variables | 20. Writing a report that summarizes the project |
| 7. Building the experiment system | 21. Presenting orally to peers and teachers |
| 8. Solving technical problems | 22. Performing peer assessment |
| 9. Performing precise measurements | 23. Teamwork (with the partner) during the performance of the project |
| 10. Processing data to obtain an answer to the inquiry question | 24. Computational modeling of the physical phenomenon (writing a computer program that performs a simulation) |
| 11. Identifying relevant sources of information (such as content sites, textbooks, or articles) for the inquiry topic | 25. Using a computerized laboratory (sensors, computer program) and technological tools |
| 12. Learning and understanding the physics content required for the project | 26. Self-managing the inquiry process |
| 13. Building a model that predicts a theoretical answer to the inquiry question | 27. Overcoming situations of uncertainty |
| 14. Linking theory to the experiment findings | |

- Are there other components that you would like to note? Please note them and write the level to which you experienced each one and the level to which it was difficult to perform. To what degree are you satisfied with the support you received?

Note that 4 lines for students' verbal response were provided after the question.

Part C - Note that 4 lines for students' verbal response were provided after each question.

- Choose at least two components you noted in which you experienced considerable difficulty. Describe the difficulty in these components. How did you cope with these difficulties?
- Choose from the list above two to three components in which you think you have developed considerably during the program. Please describe.

APPENDIX D: MAPPING THE INQUIRY COMPONENTS IN APPENDIX C TO THE FINAL INQUIRY COMPONENTS

Table IX presents the mapping of inquiry components in Appendix C to the final inquiry components.

TABLE IX. Mapping the 27 inquiry components in Appendix C to the 15 final inquiry components. One or more inquiry components were united under a single inquiry component with an inclusive name. The seven inquiry components *in italics* were included in the questionnaires at all three research stations.

Final inquiry components	Inquiry components in Appendix C
1. Choosing a topic or investigation directions	1. Choosing the topic for the project
2. Locating information sources	11. Identifying relevant sources of information (such as content sites, textbooks, or articles) for the inquiry topic
3. <i>Phrasing questions or goals</i>	2. Formulating questions about the physical phenomena the project addressed 3. Focusing the inquiry question
4. <i>Planning an experiment</i>	5. Planning an experiment system to provide an answer to the inquiry question 6. Isolating variables
5. <i>Performing an experiment</i>	7. Building the experiment system 8. Solving technical problems 9. Performing precise measurements
6. Using technological aids and a computerized laboratory	25. Using a computerized laboratory (sensors, computer program) and technological tools
7. <i>Data processing</i>	10. Processing data to obtain an answer to the inquiry question
8. Building a theoretical model	13. Building a model that predicts a theoretical answer to the inquiry question 24. Computational modeling of the physical phenomenon (writing a computer program that performs a simulation)
9. Building content knowledge	12. Learning and understanding the physics content required for the project
10. <i>Drawing conclusions</i>	14. Linking theory to the experiment findings
11. <i>Written reporting on the inquiry</i>	16. Documenting the inquiry process 19. Writing a presentation for reporting on the project 20. Writing a report that summarizes the project
12. <i>Oral reporting on the inquiry</i>	21. Presenting orally to peers and teachers
13. <i>Self-regulation</i>	4. Planning the work 13. Self-regulation 15. Examining actions performed during the project for the choice of new directions 17. Organizing the work 18. Meeting the time schedule 26. Self-managing the inquiry process 27. Overcoming situations of uncertainty
14. Teamwork with the partner	23. Teamwork (with the partner) during the performance of the project
15. Teamwork with peers in the broader group	22. Performing peer assessment

APPENDIX E: EXAMPLES OF STUDENT VERBAL QUOTES REGARDING CONSIDERABLE DIFFICULTY OR DEVELOPMENT AND EMERGENT INSIGHTS

Tables X and XI present examples of student verbal quotes regarding considerable Difficulty or considerable Development and the extracted emergent insights.

TABLE X. Examples of student verbal quotes for perceived considerable Difficulty for “data processing” and “written reporting on the inquiry.”

Perceived considerable Difficulty	
Data processing	Written reporting on the inquiry
Station 1: “Processing the findings on the computer—sometimes we get into a mess with the graphs and do not know exactly how to write the result on the computer and make a graph on the computer.”	Station 1: “Sometimes you get tied up with the graphs and do not know how exactly to write the results that derive from the graph.”
Station 2: “... then it was hard to reach more ‘complicated’ data like acceleration, by ourselves. But my partner and I succeeded by thinking which data must be taken, and we learned together how to process the data to reach more complicated data.”	Station 2: “The creation of the presentation constituted a certain difficulty primarily choosing and writing the important things, but I and my partner succeeded in dealing with this difficulty in that we were helped by our teacher-mentor and by one another.”
Station 3: “I had to use the Tracker software to produce data from the videos. This took many hours of monotonous and frequently repeated action since it was necessary to ascertain the correctness of the produced data. This caused me great frustrationI coped through the correct division of time and considerable time investment.”	Station 3: “Writing a presentation—it was hard to organize the presentation into a quarter of an hour and therefore we rehearsed the presentation to remove less important contents.”
Emergent insights	Graphs—problematic for beginners Assistance by teacher-mentor Collaborative teamwork Sustained effort and practice vital to meeting standards

TABLE XI. Examples of student verbal quotes for perceived considerable Development for “data processing” and “written reporting on the inquiry.”

Perceived considerable Development	
Data processing	Written reporting on the inquiry
Station 1: “...is a skill that has greatly developed during this year following the considerable practice of these skills, and the fact that I had to understand the logic behind the experiment so as to build graphs that explain and describe the experiment.”	Station 1: “...since in the submission of reports on experiments they are always fixed and emphasize to us what is correct, what helps us for the next times. The teachers deserve appreciation and admiration.”
Station 2: “At first we would take measurements and only after all the measurements we attempted to process and analyze them. But we understood that this is not the right thing. Therefore, we changed the planning of work and after every experiment we performed data processing and analysis for it.”	Station 2: “For two years I dealt a lot with creating a research journal and with writing detailed lab reports including: goal, description of experiment, results, processing of the results, conclusions, and factors of error. Also in organizing and summarizing the research activities in an orderly and consistent manner. I would not have improved if I had not experienced it a lot.”
Station 3: “We produced many tables and graphs from the data (from the videos we filmed) which made us professional in it.”	Station 3: “...over the year we wrote notes on all sorts of points about our work. When we sat down to write the report. we took out all the notes and they greatly helped the writing. I remember that last year we were less meticulous about this and it was really difficult to remember what we did at the beginning of the year.”
Emergent insights	Assistance by teacher-mentor Sustained effort and practice vital to meeting standards Explicit formats scaffold complex tasks Learning from past mistakes Importance of orderly consistent documentation

APPENDIX F: VERBAL DATA SHOWING STUDENTS' UNDERSTANDING OF CONSIDERABLE EXPERIENCE, DIFFICULTY, AND DEVELOPMENT

In Table XII we offer evidence from a selection of student responses to the open questions regarding Difficulty and Development that the facets of meaning we attributed to these aspects (Sec. IV, 3rd paragraph) were echoed in students' verbal comments. Although there was no required verbal response regarding the Experience aspect, we were able to extract from students' previous verbal responses facets of the Experience aspect that correspond to the facets of meaning we attributed to that aspect.

TABLE XII. Facets of student meaning attributed to considerable Difficulty, Development, and Experience as expressed in verbal comments in open questionnaire items. Sample students' quotes are presented against each facet of meaning.

Considerable Difficulty	
Sense of struggling to achieve efficacy	"Processing the findings on the computer—sometimes <i>we get into a mess with the graphs and do not know exactly how to write the result on the computer and make a graph on the computer.</i> "
Feeling challenged	"Oral presenting in front of others, in my opinion, this really developed in me because <i>I had a real fear and anxiety of speaking before an audience.</i> "
Awareness of frustration in attempting to perform	"I had to use the Tracker software to produce data from the videos. This took many hours of monotonous and frequently repeated action since it was necessary to ascertain the correctness of the produced data. <i>This caused me great frustration.</i> "
Feeling of being unable to perform or needing/requesting help	"The oral presentation: <i>I have difficulty with standing in front of an audience and presenting. The attempt at coping with this did not really succeed</i> " "The creation of the presentation constituted a certain difficulty primarily choosing and writing the important things, but I and my partner succeeded in dealing with this difficulty in that <i>we were helped by our teacher-mentor and by one another.</i> "
Considerable Development	
Awareness of becoming more proficient and skilled	"The presentation of the project—I was pressured when we needed to submit and present the work in front of the teacher-mentors and examiners from the Institute, but <i>over time and with the many presentations we performed I began to overcome the fear.</i> "
Being able to select a variety of action paths, mobilize resources and perform more efficiently	"Writing a presentation—it <i>was hard to organize the presentation into a quarter of an hour and therefore we rehearsed the presentation to remove less important contents.</i> "
Feeling of progress from novice to expert in one's thoughts and actions	"Oral presenting in front of others, in my opinion, this really developed in me because <i>I had a real fear and anxiety of speaking before an audience.</i> From year to year, the pressure and anxiety have decreased, and every additional presentation improved my feeling of confidence and ability of speaking in front of an audience." "At first we would take measurements and only after all the measurements we attempted to process and analyze them. <i>But we understood that this is not the right thing. Therefore, we changed the planning of work</i> and after every experiment we performed data processing and analysis for it."
Awareness of ability to reflect on one's thoughts and performance and re-construct one's beliefs when necessary	"We <i>understood that the results were not wrong</i> and we needed to draw conclusions why our experiment results were different from the theory. After many repeated experiments, we found the error sources that greatly influenced the results and we reached additional conclusions that explained our results." "There was <i>a difficulty in the comparison between theory and experiment</i> since there is a large gap between the theoretical world and the realistic world, and therefore we needed to think and to critique what we did and to investigate further to reach more correct conclusions and this developed us in the skill of drawing conclusions ..."

(Table continued)

TABLE XII. (Continued)

Considerable Development	
Perceiving oneself as becoming a member of the inquiry community of practice	“Choosing a topic—we changed the topic of the work since <i>during the investigation of the initial topic we encountered a strange phenomenon that we did not expect and that interested us...It made me realize that inquiry is dynamic</i> and there is no need to panic about it, but to deal with being flexible with the investigation and in the end knowing how to choose and focus on the topic you have chosen.”
Considerable Experience	
Frequent engagement in performing the IC	“Over time and with the many presentations we performed”; “my team partner and I had to work <i>continuously and consistently</i> ”; “with time <i>we phrased a large number of questions.</i> ”
Estimate of much time spent in performing the IC	“For two years I dealt <i>a lot with creating a research journal and with writing detailed lab reports</i> ” “ <i>This took many hours of monotonous and frequently repeated action.</i> ”
Awareness of repeatedly performing the IC	“Following <i>the considerable practice of these skills</i> ”; “ <i>We produced many tables and graphs.</i> ”; “ <i>We performed many experiments.</i> ”

APPENDIX G: HIGH OR LOW RATING EXAMPLES

Table XIII presents the general rule for High or Low rating of aspects related to given inquiry components: if the relative frequency of an aspect was equal to or exceeded the mean relative frequency for at least two of the three stations, the rating for that aspect would be High. Otherwise, it would be Low.

TABLE XIII. Examples of High/Low rating of the seven core inquiry components that were included in all three research stations (mrf = mean relative frequency).

Inquiry component	Aspect	Station 1	Station 2	Station 3	Rating
Phrasing questions or goals	Experience	Above mrf	Above mrf	Above mrf	High
	Difficulty	Above mrf	Above mrf	Above mrf	High
	Development	Above mrf	Above mrf	Above mrf	High
Planning an experiment	Experience	Above mrf	Above mrf	Above mrf	High
	Difficulty	Below mrf	Below mrf	Above mrf	Low
	Development	Below mrf	Below mrf	Below mrf	Low
Performing an experiment	Experience	Above mrf	Above mrf	Above mrf	High
	Difficulty	Below mrf	Below mrf	Above mrf	Low
	Development	Above mrf	Above mrf	Above mrf	High
Data processing	Experience	Above mrf	Above mrf	Above mrf	High
	Difficulty	Below mrf	Below mrf	Below mrf	Low
	Development	Above mrf	Below mrf	Below mrf	Low
Drawing conclusions	Experience	Above mrf	Above mrf	Above mrf	High
	Difficulty	Above mrf	Above mrf	Above mrf	High
	Development	Above mrf	Above mrf	Above mrf	High
Written reporting on the inquiry	Experience	Below mrf	Below mrf	Above mrf	Low
	Difficulty	Below mrf	Below mrf	Below mrf	Low
	Development	Below mrf	Above mrf	Above mrf	High
Oral reporting on the inquiry	Experience	Below mrf	Above mrf	Above mrf	High
	Difficulty	Above mrf	Above mrf	Above mrf	High
	Development	Below mrf	Below mrf	Above mrf	Low

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