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High school students' perceptions on the relevance of inquiry-oriented instructional labs as introduction to an extended research project

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Inquiry practices can be integrated into various settings that differ in terms of their constraints and hence in the scope and depth of the practices that students experience. Key policy papers suggest implementing a gradual learning sequence for inquiry practices so that students' learning experiences in more constrained settings can serve them later in extended research projects. What type of learning progression in inquiry is valued by students? To answer this question, students' views were examined while progressing from inquiry-oriented instructional labs to an extended research project. This was done in the context of the Research Physics program, a three-year program consisting of an introductory stage followed by a long-term (~18 months) research project. The group administered interactive questionnaire methodology was used to collect student reflections at the interface between the two stages of the program, both individually and in groups. Students were asked to identify inquiry practices they had encountered during the introductory stage and to evaluate their contribution to their projects. Findings showed that while students perceived the development of measurement, analysis, and self-monitoring skills as useful in preparing them for future research projects, this was not the case for the practices of teamwork and communication of knowledge. We explain these findings, using the boundary crossing theoretical lens, by looking at the different meanings these two practices take on when imported from the physicist's lab to the educational lab and suggest that this impedes the cultural boundary crossing between these two settings.

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I. INTRODUCTION

Central policy documents have suggested standards for better integration of experimental inquiry practices into a range of physics courses, from high school physics courses [1,2] to introductory and advanced laboratories serving college and university students [3]. Based on research in the physics education field we identify 4 types of laboratory settings students can engage in:

i. traditional instructional labs
ii. inquiry-oriented instructional labs
iii. extended research projects
iv. research apprenticeships

Settings iii and iv are longer compared to i and ii. Settings iii and iv differ in the context and environment in which the research is conducted. Research apprenticeships are commonly carried out at a scientific research laboratory and the research questions investigated are considered open to the scientific community, while extended research projects are conducted in advanced instructional labs that provide students with resources that allow them more autonomy in constructing their experiments. The problems investigated are open ended from the students' perspective [4,5]. This study examines students' perceptions of the relevance of inquiry-oriented instructional labs (setting (ii) to their preparation for extended research projects (setting iii).

The same students often engage in experimental practices in more than one setting, differing in the scope of the cognitive tasks and autonomy that they experience in each setting [6]. For example, students who experience experimental work in an introductory-level traditional lab course, consisting of tightly prescribed labs, may later attend research apprenticeship programs in which they take part in the work of a research group in an academic institution [6,7].

The transition of students between different experimental settings raises several important questions. How do students perceive the relationship between the experimental practices they have experienced in different settings? How do they perceive practices and views shaped in one setting to serve them when operating in a different one? Does their prior experience serve the latter?

Answering these questions can inform the design of inquiry learning progressions [3,8] that support a gradual development of experimental practices across different settings and empower more students to participate in advanced research experiences.

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A. Boundary crossing in educational settings

Students' transition between experimental settings can be examined using the theory of boundary crossing. Science education researchers describe participation in science classes as a cross-cultural event [9,10]. Students, who are grounded in their "everyday" culture, are required to adhere to the norms and practices of the science classroom culture. Here, culture refers to the anthropological definition: "*an ordered system of meaning and symbols, in terms of which social interaction takes place*" [11]. The culture shapes the norms, values, beliefs, expectations, and conventional actions or practices of its members [12].

Students come to class with their values, norms, and practices as shaped by their everyday culture which often clash with the science classroom's culture [13]. For example, students often loosely claim that the acceleration of a pendulum bob at the end of its swing is zero, because speed is zero. As analyzed by Reif and Larkin [13], it is not only that the notion of acceleration has different meanings in everyday life and in physics, but that these differences arise because the practice of validation has different meanings in the different domains. In everyday life, validity is based on intuition: students tend to accept commonsense notions without carefully checking them as they are quick, useful, and meet everyday life goals [14]. However, in the scientific culture, validation of knowledge is pursued to achieve the central goal of effective prediction and explanation. Scientific validity must be carefully and formally checked, and its criteria are well specified [13]. This difference of practice between cultures can lead students to reject a valid scientific assertion (the acceleration of a pendulum bob at the end of its swing is nonzero, though the speed is zero) because it does not meet their everyday intuitive way of reasoning and validating explanations.

The differences between cultures which inhibit a smooth transition between them are described in the literature as boundaries: "*The boundary in the middle of two activity systems represents the cultural difference and the potential difficulty of action and interaction across these systems*" [15]. In the previous example, the boundary is the difference between the practice of "validation" in the two cultures, which impedes the students' transition from one to the other. Boundaries, however, represent not only areas of discontinuity, conflict, or misunderstanding, but also areas of significant learning potential. When boundaries are met and explicated, learning can take the form of identifying new perspectives and expanding one's point of view [16,17], which is referred to as boundary crossing [15]. Boundary crossing can be smooth when the two cultures are largely congruent (i.e., share norms and values) or it can be rough or even impossible when they are not [10]. It is important to note that boundaries can be actual or perceived differences [12].

The various experimental settings are designed to help students develop as scientific researchers. This is a process of enculturation: students rooted in their school culture are required to adhere to the norms and practices of the research laboratory. Research in physics education focuses on how best to mirror authentic research practices to the students [18], offering settings that are in-between the two cultures. These settings may differ in terms of the norms and practices that educational designers choose to reflect to the students. Therefore, students who progress from traditional instructional labs to inquiry-oriented labs, extended research projects, or research apprenticeships may experience discontinuities in their learning. How is the transition between different experimental settings viewed by students? What discontinuities do they perceive between settings, and how do they echo cultural tensions between the school and the scientist's lab?

B. Students' perceptions of experimental practices across different settings

Extensive research on teaching and learning in the introductory level physics laboratory has dealt with students' practical work and concept learning whether in high school [1,19] or at the undergraduate level [20]. In recent years researchers have developed tools to further investigate students' views of the nature of experimental investigation [21,22] and students' agency regarding various experimental practices [6]. Studies of students' views in the introductory lab context [22–25] reveal a gap between students' perceptions of the nature of experimental physics and expertlike perceptions and call for reform of traditional lab instruction.

One of the most prominent responses to this call are inquiry-oriented instructional labs. These labs are embedded in the lab section of introductory physics courses and aim to give students more autonomy in the core practices of the scientific research process. A notable example of such a setting is ISLE [26]—where students design and conduct observational and testing experiments that are characteristic of the work of scientists. Another notable example is SQILabs [27]—labs that focus on and problematize specific inquiry practices (e.g., measurement and evaluation of uncertainty).

Studies conducted in inquiry-oriented instructional labs and project-based courses show that the autonomy granted to students and their firsthand engagement in wider aspects of inquiry positively influence their experience and their perception of the nature of scientific research [18,24,28,29]. Students' sense of ownership was also studied in these settings. Findings demonstrate that ownership can increase over time even without the students' initial interest in the project, and that ownership can fluctuate during the challenging work on a multiweek project [30]. A positive correlation was found between students' conceptions of the nature of science and their sense of self-efficacy and ownership [31,32].

A few studies have examined the differences between students' perceptions in different experimental settings. Holmes and Wieman [6] compared students' identification of experimental practices they encountered in structured lab courses, design lab courses and undergraduate research experiences (URE). They found high correlations between students' reports of their undergraduate research experience and the cognitive tasks that characterize authentic research. The elements lacking from the URE were establishment of research goals and evaluation of results. In the design lab courses, students reported that they did establish research goals but did not determine the feasibility of the experiment, evaluate the results, or present their work. Only a few students mentioned that the lab notebooks helped them communicate their results. Almost all components of authentic research were absent from the introductory labs, except for data collection and analysis.

Wilcox and Lewandowski [33] conducted a longitudinal study of students' perceptions of the nature and importance of experimental physics as they advanced through multiple courses in the undergraduate lab curriculum. They found that although students' average survey score increased (more expertlike views), deeper analysis revealed that this did not reflect students' improvement in the course sequence but rather selection: the students who progressed to the advanced labs were those who already held more expertlike views.

Stanley and Lewandowski [34] examined the development of scientific communication and specifically of the practice of scientific documentation from undergraduate courses to graduate research. They found that even students who had written laboratory journals in their earlier undergraduate labs reported that their experience was ineffective and did not serve them in their advanced research because the design of the structured labs did not necessitate the use of lab journals. Students explained that this was due to the short time span of the activities and their structured nature: there was no continuity between sessions and thus no opportunity to revisit measurements; in other words, there was no real need to keep a journal. This finding can be interpreted as a student-perceived boundary between undergraduate and graduate labs, indicating the need for boundary crossing pedagogy regarding scientific documentation.

The transition between high school and undergraduate practical work was studied by Sneddon *et al.* [35]. Surveys and interviews were used to articulate the views of undergraduate physics students about their high school labs. The study was conducted shortly after the students graduated and showed that the students perceived their early practical work as a positive experience that they found useful, understandable, and enjoyable. The authors called for university faculty to build on the positive experience in school. However, when drawing conclusions about students' claims in favor of their lab experiences we should consider Abraham's [36] caveat—students may only be referring to the "hands-on" nature of these labs, as these labs are often less cognitively demanding and therefore positively evaluated by students with little interest in science.

II. RESEARCH GOALS AND APPROACH

The literature reviewed above indicates that there can be a discontinuity in learning across different educational lab settings. This study aims to contribute to this body of research by describing the boundaries reflected in students' perceptions of the usefulness of inquiry-oriented instructional labs to later work on an extended research project. We present a case study of a national program entitled Research Physics (RP) that included two stages: a year-long introductory stage consisting of short, structured, inquiry-oriented activities focused on specific inquiry practices, followed by an extended research project in which students were given autonomy over most aspects of the research. A reflective activity, conducted three months into the project stage, was designed to study the transition between the two settings by probing students' views on the impact of their introductory stage experience to their current project work.

The RP case study also served to examine the value of the instructional design in the eyes of the students, which progressed from inquiry-oriented structured labs to extended research projects. This design followed the approach of several position papers [3,37] that advocate engaging students in structured activities that involve a narrow range of research practices before they carry out a comprehensive research process. Others have suggested to engage students from the very beginning in the holistic process of research [38], even though this would limit the scope of investigations to relatively simple phenomena that students can approach with their conceptual knowledge and acquired tools.

To portray students' views on the transition between the stages, the following research questions were examined:

1. Which inquiry practices were identified by students as central to the introductory stage activities?
2. Which of these practices were perceived as useful for their extended research projects, which were not perceived as useful, and why?

III. CASE STUDY—THE RESEARCH PHYSICS PROGRAM

The RP program is a new school subject initiated by the national Ministry of Education in Israel [39] which is intended for capable and interested students concurrently enrolled in high school physics. The high school physics course is an elective that spans 3 years from 10th to 12th grade, covering a syllabus equivalent to that of an algebra-based introductory college course. The RP program consists of two stages: (a) a 1–1.5 year introductory stage intended to teach fundamental practices and perceptions about research and (b) a 1.5–2 year extended research project stage. The program awards matriculation credit based on the student's lab portfolio, which is assessed by the student's project advisor, and on an external examination of the written report and oral presentation of their research. The program is implemented in schools and regional science centers and targets ∼2% of all physics students in the country.

In terms of curriculum, the educational ministry only provided general guidelines for learning goals, thus allowing instructors some latitude in designing their own curriculum and the learning sequence in which the research practices are introduced.

Only teachers who are certified as research advisors can teach in the RP program. Two national institutions certify high-school physics teachers as advisors: the Acheret Center [40] and the Department of Science Teaching at the Weizmann Institute of Science. This study focuses on the implementation of the RP program in a regional class held at the Weizmann Institute from 2016 to 2018. This class also served as a professional development workshop in which teachers were trained to instruct students in extended research projects.

The design guidelines underlying the syllabus chosen for the regional class and the resulting instructional sequence are discussed in detail in the following sections. Referring to the classification of laboratory settings presented in the introduction, the introductory stage of the program corresponds to inquiry-oriented instructional labs described in the literature (setting ii), while the advanced stage corresponds to extended research projects (iii). To clarify the characteristics of these settings, we will describe them in comparison to more familiar settings: traditional instructional labs (i) and research apprenticeships (iv).

A. Introductory stage design

As mentioned above, the RP program is intended for capable and interested students. However, the introductory stage is meant to take place within the high school physics class, thus allowing all students to experience inquiry. Students who express interest in the program can proceed, depending on their achievements, to conduct an extended research project. Hence, the introductory stage should provide students with the foundations of scientific inquiry while considering the embedded constraints of the regular physics course such as limited resources and technical assistance in high school labs, high student-teacher ratio, short periods of time, etc. Similar constraints characterize inquiry-oriented instructional labs at the university level, as described in the literature, that inspired the design of the RP introductory stage.

Inquiry-oriented instructional labs are embedded in the lab section of introductory physics courses. These settings were designed in response to studies criticizing students' experience in traditional labs that included the limited agency granted to students [41,42] and the disparity between students' and practicing physicists' ideas about experimental physics [43]. Other studies have shown these labs do little to enhance student understanding of lecture content [20].

Inquiry-oriented labs aim to give students more autonomy in the core practices of the scientific research process than in traditional, tightly prescribed instructional labs. Smith *et al.* [44] pointed out that granting autonomy to students does not necessarily mean less structuring but rather adding structure ("turning instructions into questions") that enable execution and reflection in stages that were usually carried out for, rather than by, the students. This approach is consistent with the call for lab instruction to be better situated on the continuum between tightly directed labs and completely unstructured situations [45]. Accordingly, the RP program adhered to cognitive apprenticeship design guidelines, including structuring and problematizing scaffolds to support students' learning [46].

Structuring can center on different aspects of inquiry. For example, the ISLE approach [26] involves students in planning and carrying out experiments that characterize scientists' work, such as observational experiments and testing experiments. Students are asked to identify patterns in phenomena, propose possible explanations for their observations, plan experiments to test their explanations, and revise their explanations in the light of the experimental outcomes. Another approach is to problematize specific inquiry practices, for example, measuring and assessing uncertainty (in the "structured quantitative inquiry labs" [27]), or on experimental design issues (in the "restricted inquiry labs" [47]). Research shows that such inquiry-oriented settings positively affect students' ability to design and interpret experiments, their beliefs about the nature and importance of experimental physics, and their confidence and motivation to "do physics" [26,43,48].

Given these examples, the regional class was designed to structure activities that grant more agency to students in the following practices:

1. Defining and focusing research questions
2. Constructing an experimental setup
3. Selecting and operating measurement tools
4. Data analysis
5. Constructing theoretical models
6. Self-monitoring of work
7. Teamwork
8. Communication of knowledge

These practices served as the RP learning goals and were intended to present three aspects of scientific research to the students: the investigation process (practices 1–5), engagement in the scientific community (practices 7–8) and self-regulation of a complex process, reflecting research as an iterative process of finding a solution to an ill-defined problem (practice 6). A gradual learning progression was designed: activities increased in length from 1 session activities (4 h) to activities lasting 2–4 sessions. More importantly, the activities gradually increased students' agency including the scope of decisions they oversaw and the amount of self-regulation required while working towards the completion of the tasks. Accordingly, the initial tasks were relatively well defined whereas later on the activities were relatively ill defined. Many of the activities involved explication and reflection on epistemic views related to the experimental practices. The design of the activities followed Reiser's [46] approach to the scaffolding of learning as involving structuring as well as problematizing actions, as illustrated in the first activity entitled "keep on moving (the cart)," that was designed in three stages:

1. Students were asked to devise a setup in which a cart moves at constant speed and to provide experimental evidence that the speed is indeed constant. Students suggested a variety of methods such as placing the cart on a slightly inclined plane to adjust for friction, or to have a mass hanging from a pulley pulling the cart. This contrasts with traditional lab structuring, where students are given a system and are instructed on how to achieve the desired motion.
2. The ticker-timer apparatus was introduced, and students were requested to provide evidence that their cart moved at a constant speed using the dot diagrams produced by the ticker timer as well as measure that speed. Students either averaged the different distances over time between consecutive dots or focused on two dots in the portion where the distances seemed even. This contrasts with the traditional lab, where students receive step-by-step instructions for reading the data from diagrams.
3. Students were asked to represent the observed motion graphically, with no further instructions as to how to do so. Many students constructed the linear graph they were acquainted with from the study of kinematics ($x = x_0 + vt$),where the slope represents the previously measured speed; hence ignoring the actual ticker-timer measurements that fluctuated. Specifically, they used the measurement model [49] to extract the average speed but abandoned it and used the theory-based model to represent the whole motion.

The structuring of the activity in three distinct stages, where the third one allowed both theoretical and experimental models to emerge, served to problematize the epistemic aspect which involved discussing the distinctions between theoretical and experimental models. Later activities, examples of which are described in the Appendix, followed similar design guidelines.

The first year of the introductory stage ended with a "miniproject," consisting of an inquiry project lasting 16 h which the students presented to their peers and advisors. Students were responsible for all stages of the miniproject, from choosing and refining their research questions all the way to presenting their findings. However, their inquiry was mainly phenomenological. The students did not construct theoretical models for phenomena that are consistent with the experimental data. A few groups compared their findings to derived formulas or to experimental results found on the web.

During the first three months of 11th grade (~32 h) the students learned to construct computational models in VPython, following tutorials that introduce programming hand in hand with physics concepts [50]. After learning Euler's method and how to materialize it in the programing environment, the students were required to model on their own the motion of a mass on a spring and motion under a central force, while coached by the instructor. In their last computational unit students were guided to compare their numerical model to experimental measurements of falling paper cups and refine the model to better match experiment.

B. Extended project stage design

The RP project stage was inspired by advanced project-based courses described in the literature [4,51–53]. These settings engage students in extended research projects, lasting from several weeks up to more than a year, allowing students to explore problems at the forefront of their knowledge and to take control over many of the research process steps. According to educational ministry policy [39], RP projects should be carried out in pairs in well-equipped labs in schools or regional science centers, under the supervision of physics teachers. As physics teachers are rarely experienced researchers, they are required to participate in meetings of a community of advisors led by an academic coordinator, where they share their experiences and discuss possible pathways to respond to upcoming dilemmas [47].

This unique design of apprenticeship [4] differs from the more common model of research apprenticeships in authentic research labs [5] in several ways: (a) The novelty of the topic under investigation: in research apprenticeships the problems studied are at the forefront of scientific knowledge and serve to expand this knowledge, while in RP the problems investigated are at the forefront of students' knowledge but have usually been solved by the scientific community. (b) Students' agency: in a research lab it is the scientist's role to choose a research topic, formulate the research question, design the experimental setup, etc. Students commonly carry out marginal roles of data collection and analysis [54] and do not engage in the epistemic aspects of planning and monitoring the research progress [5].

In contrast, in the RP project the students are responsible for most roles, and the teacher-advisor works alongside them. When encountering challenges, the teacher-advisor takes the role of a senior member in the research team, in terms of their broader knowledge base and their strategic approach to cope with the challenges. However, rather than providing solutions, advisors are expected to model their strategy explicitly or to direct the students where to look for solutions. Thus, the cognitive apprenticeship model [55] is better materialized in RP projects, as students experience modeling and coaching across the whole process of designing an experiment, constructing a theoretical model, comparing it to the measurement model and making modifications when needed. Students get multiple opportunities to experience aspects of self-regulation, both individually and in groups.

To support the research teams in monitoring their progress, the teacher-advisor community structured the RP project as a series of milestones:

1. Research selection “fair”: the students were presented with an array of phenomena and were guided in the selection of a feasible research topic.
2. Research proposal—two months into the project.
3. Interim report—at the end of 11th grade.
4. Final report—towards the end of 12th grade.
5. Final presentations and summative assessment.

The current study examined students’ views as to the contribution of their experience in the introductory stage to their extended project work. Students were three months into their project work, after probing their phenomenon of interest and conducting preliminary investigations and after submitting their research proposals. We sought to find out whether they experienced a smooth transition between the program stages or whether they experienced discontinuities due to the design of the two stages of the program.

IV. METHODOLOGY

A. Data collection

The design of the data collection tool followed the guidelines of the group administered interactive questionnaire (GAIQ, [56]), that was adapted to examine students’ views on the value and usefulness of the research practices introduced in the introductory stage to their project work. The tool made use of group discussions to accomplish the following goals: (a) Create a common language—a shared inventory of inquiry practices the students experienced, triangulated by individual and group data collection stages. (b) Encourage introspection and clarification of meaning by respondents by having them work in groups and categorize some of the data themselves. (c) Bypass researcher interference in discussion to minimize distortion in data collection due to personal bias.

The adapted GAIQ was composed of the following steps:

1. The teacher summarized the activities that took place in the introductory stage.
2. Individually, the students listed inquiry tasks they encountered[1] during the introductory stage activities (e.g., “coping with a scientific text” or “presenting in front of the class”).
3. In groups of 3–5 (8 groups overall), students combined their inquiry tasks into one unified list, classified them into categories of their choice and labeled these categories (see Fig. 1). These categories are referred to as “student made categories.”
4. Individually, the students answered 3 questions on the categories that their team produced:
    - (a) Which of the categories your group generated are the most important to learn during the introductory stage? Why?
    - (b) Which categories should be learned only when working on the extended projects? Why?
    - (c) Which categories are irrelevant to the program? Why?

Thirty-two 11th grade students (12 females, 20 males) from six different home schools and mostly middle-class families participated in the adapted GAIQ. They were participants of the second year of the regional RP class at the Weizmann Institute, that were selected from the 54 students who completed the first year. Selection was based on their commitment (attendance, completion of tasks and participation in classroom discussions) rather than their achievements. All students were also enrolled in an advanced physics course in their high schools.

In order to investigate students’ transition between program stages, data collection had to occur at a point in time when students still remembered the introductory stage experience but had already gained sufficient experience in the extended project to be able to reflect on the sequencing of these two stages. Accordingly, it was positioned after the students had completed the introductory stage (in 2016–2017) and were three months into their projects, after they had submitted their research proposals. Their position in between the two stages of the programs enabled them to reflect on the relations between them.

To motivate students to answer the questionnaire, it was explained to them (orally and in writing) that the goal of the process was to reflect on their preliminary learning experiences and to clarify for themselves what is crucial to know in order to conduct research. The process lasted 1 session (4 h). The GAIQ was administered by one of us (D.P.), who served as the coordinator of the RP program. The research advisors did not participate in the session.

B. Data analysis

Eight groups of students participated in the GAIQ; each formulated different categories of inquiry practices containing practices they encountered in the introductory stage. To analyze these student-made categories, a set of top-down categories that reflected the learning goals set for the program were constructed. The correspondence between student-made and top-down categories was determined via the following steps:

1. Top-down categories were formulated corresponding to the program learning goals:
    - (a) Defining and focusing research questions
    - (b) Constructing an experimental setup
    - (c) Selecting and operating measurement tools
    - (d) Data analysis
    - (e) Constructing theoretical models

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[1] We did not directly ask students to list central inquiry practices or skills as the term “practices” is nonstandard in Hebrew and would lead to alienation from the reflective activity, and the term “skills” has an algorithmic meaning.

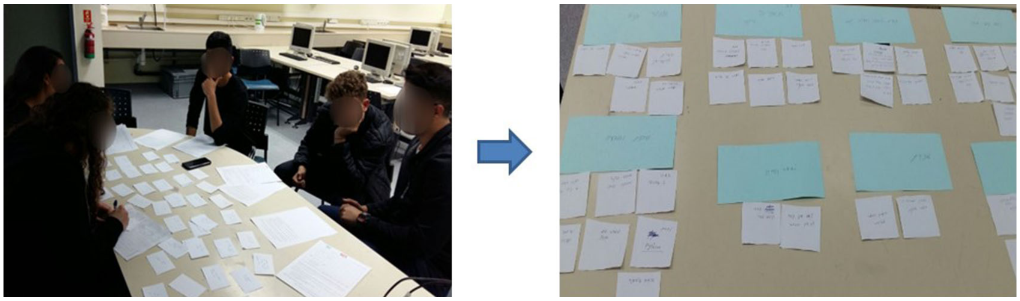

FIG. 1. Step 3 of the GAIQ: students creating a unified list of inquiry tasks they encountered during the introductory stage (left) and categorizing them (right). Students used labeled tabs to facilitate the sorting process.

   (f) Self-monitoring of work
   (g) Teamwork
   (h) Communication of knowledge
2. Each top-down category was detailed, using components that the students outlined as well as components that the researchers added based on the educational literature, representing the researchers' understanding of the content of the top-down categories. For example, the top-down category "constructing theoretical models" was broken down into the following components: Theory, equations, reading articles, comparison (of theory and experiment), modeling, computational models, numerical solution.
3. Correspondence between top-down and student-made categories was determined in terms of the overlap in components. In particular, we examined
   (a) Which student components corresponded to the category?
   (b) How many groups did these components appear in?
   (c) How many groups identified the top-down category as a distinct category as well?

The categorization of students' components was done by the first author (D. P.). Categorization was examined by a second researcher (E. Y.) for ∼20% of the data. Disagreements were discussed and resolved, resulting in almost 100% interrater reliability.

Note that the label students used for each category was not used to match the student-category with the top-down category, but the components included in it: If at least half of the components in a student-category corresponded to the top-down category, a match was declared. For example, group 8 classified the following components under the practice they labeled "*understanding the subject*":

1. *Understanding the meaning of a physical problem*
2 *Dealing with theory*
3 *Learning to write codes*
4 *Development of equations and formulas*
5 *Comparison to theory*

Since three out of five components (2, 4, 5) corresponded to the components of the top-down category "constructing a theoretical model," this student-made category was considered to correspond to the top-down category, although the category name, as well as component 1, were ambiguous. This process served to answer the 1st research question; namely, which inquiry practices students identified as central to the introductory stage activities.

Once the correspondence between top-down and student-made categories was established, we examined students' attitudes regarding the contribution of each category of practices to their future research experience, to answer the 2nd research question: Which of these practices were perceived as useful for their extended research projects, which were not, and why?

If students perceived their experience with certain practices in the introductory stage as irrelevant to their project work, this would point to boundaries between these settings that hinder the transfer of acquired practices.

V. FINDINGS

Table I presents the analysis results for the correspondence between student-made and top-down categories (in response to research question 1):

As shown in Table I, most groups identified categories 2–4 and 6–8, namely, constructing an experimental setup, selecting and operating research tools, data analysis,

TABLE I. Correspondence between top-down and student-made categories ($N = 8$).

Top-down categories	Number of groups with corresponding categories
Defining and focusing research questions	0
Constructing experimental setup	5
Selecting and operating measurement tools	6
Data analysis	5
Constructing theoretical models	3
Self-monitoring of work	5
Teamwork	6
Communication of knowledge	5

self-monitoring, teamwork, and communication of knowledge as central practices in the introductory stage of the RP program. These findings are consistent with the design of the introductory stage activities that indeed focused on introducing these experimental practices and gradually increasing autonomy of students.

In contrast, there was a weak correspondence between categories 1 and 5 (constructing a theoretical model, defining and focusing research questions) and the student-made categories. Although these practices are more relevant in long-term settings, as they allow for processes of refining the research topic and building and revising a theoretical model to match the experiment, this finding is important since the development team did indeed attempt to engage students in these practices to some extent during the introductory stage.

To answer research questions 2 and 3, further detailing of student-made categories and their components, as well as the students' reasons in favor of their inclusion or noninclusion in the introductory stage is presented in the following sections.

A. High correspondence categories

1. Selecting and operating research tools

Students identified selecting and operating research tools as a central practice in the introductory stage of the program: the inquiry component lists of all eight teams contained many components corresponding to this category. Six out of the eight teams considered it to be a distinct category. Table II shows the different labels these six teams gave to this category and representative examples of inquiry components that they included:

TABLE II. Student-categories corresponding to the top-down category "research tools" and examples for components included in them.

Group number	Category name	Example of components included in category
1	*Useful tools in research*	*Using the Moodle system* *Using the sonar*
2	*Working with devices*	*Using a camera* *Using sensors*
4	*Using unknown technology*	*Introducing new instruments and measuring tools* *Using the computer*
5	*Technical tools*	*Learning new programing language* *Video analyzing in Tracker*
7	*Platforms and measures*	*Using Audacity* *Using Pasco Sensors*
8	*Technical work*	*Working on Excel, PPT, Word* *Working on Google drive*

An examination of the components included in this category shows that the research tools are described in terms of their names (e.g., "tracker", "sonar", "Pasco sensors") rather than their function or mechanism. Students included various tools associated with data collection (sensors), analysis (Excel), construction of theoretical models (programming), or communication (PowerPoint, Word).

Most of the students in these six teams (16/23) identified this category as one that should be part of the introductory stage. Students provided the following reasons for supporting the introduction of the "research tools" category in the foundation stage:

1. Using various tools is an integral part of research (7 students): *"Using technology is a major part of the process of investigation, data collection and drawing conclusions"*
2. Introducing a variety of tools enables an informed choice of suitable research tools in the project, increasing the precision and effectiveness of experiment (7 students):

   "In order for us to have a number of options to measure, with different tools, so that our range will be wider for the big project"

   "Getting to know different devices—so we know what to work with and where to turn when we want to produce reliable data".

Only one student argued that it should rather be taught during the work on the extended project since during his project work he did not utilize many of the tools presented in the introductory stage.

These findings mesh with a dilemma that was considered in the design of the introductory activities: should a wide range of research tools be introduced even though only some will be used in their future projects, or should there be a "learn-as-you-go" approach, since every project uses a different set of tools, and the students should be allowed to master each tool when the need arises as each project unfolds? The findings imply that the students appreciated the design of the introductory stage that exposed them systematically to a large range of tools, even though some of them would not be used in their future work, since it heightened their ability to choose the appropriate tool for their research. In this case, boundary crossing between stages was smooth.

2. Constructing an experimental setup and data analysis

Students identified both constructing the experimental system and data analysis as central practices in the foundation stage of the program: all the teams' lists contained several inquiry components corresponding to these categories and most teams made them distinct categories (5/8 groups for each practice).

Nine out of the nineteen students in the groups that identified the category constructing the experimental system claimed it was an important practice to engage in during the introductory stage, and 6/20 stated the same for the data analysis category. The other students did not refer to these categories in their individual questionnaires. None of the students believed that these practices were irrelevant to the introductory stage or that they should be learned during the extended projects. The students' reasoning was straightforward: constructing the experimental setup and analyzing data are main steps in the inquiry process; hence, they should be part of the introductory stage. However, they did not explain why these practices should be experienced before taking part in a research project:

"*Without a functioning system, you will not be able to perform experiments and understand the subject through them.*"

"You must learn how to conduct an experiment before working on a large project."

These findings imply that the students thought that these practices can be acquired outside of the extended project context. They considered it to be beneficial to experience them before carrying out their research project.

3. Self-monitoring of work

Students recognized "self-monitoring" as a central practice in the introductory stage of the program: all the teams' lists contained inquiry components corresponding to this category, and 5/8 teams made it a distinct category. Most students in these groups (13/19) identified self-monitoring as a practice that should be part of the introductory stage, as it is relevant for their ongoing projects. Only one student argued that it should be learned while working on the extended project since in his opinion self-regulation is only acquired better when work is really open-ended and independent, and not in structured activities. The students provided the following reasons for incorporating self-monitoring in the introductory stage:

1. Self-monitoring and independent learning are key practices in scientific research (6 students): *"The most important is the development of self-learning abilities. Because long-term research requires a lot of self-learning and this is an important skill to acquire before starting long-term research."*

   "In all types of research we will have to deal with managing time pressure."
2. To meet the challenges of the RP program (3 students): *"So that we will learn to function under time pressure that will increase in the coming years".*

   "The higher the level, the higher the level of functioning required from us. Therefore, project management will be beneficial."
3. Self-monitoring leads to greater ownership of the process (1 student): *"You need to deal alone with problems and not ask for the answer in order to develop curiosity and satisfaction once you succeed."*

As mentioned above, one of the main dilemmas with respect to the design of the RP program was the tradeoff between authentic apprentice learning and managing the cognitive load on the students. The development team was concerned that structured activities could undermine the independence and self-regulation abilities of the students as well as the students' perception of the importance of self-regulation to research. The findings show that despite the structuring of the introductory activities, the students identified self-monitoring as an important component of the intervention and as a basic component of scientific inquiry that could and should be acquired in a gradual learning progression.

B. Low correspondence categories

There was a weak correspondence between the top-down category "constructing a theoretical model" and the student made categories, as 3/8 teams identified it as a distinct category. Table III presents the different labels these teams gave to this category and examples of the inquiry components that were included.

Among the students in the teams that identified "constructing a theoretical model" as a distinct category, only 4/12 stated it was important to learn during the introductory stage, as it is a central research practice. Four out of the 12 others claimed it should be learned during the project stage. Their main reason was that the theoretical aspect is unique to every project and therefore cannot be learned in advance:

> *"Since the understanding of the subject is specific to each project, it is unnecessary to learn in the 10th grade. In other words, in order to demonstrate research methods (what I think is most important in the 10th grade) you need a subject for investigation, but it is only an accompaniment, so I think it's unnecessary to delve into it."*

TABLE III. Student categories corresponding to the top-down category "constructing a theoretical model" and examples for components included in them.

Group number	Category name	Example of components included in category
2	*Compatibility with theory*	*Comparing results to theory linearization*
6	*Understanding the subject*	*Developing equations and formulas comparison to theory learning to write codes*
8	*Finding connections between theory and reality*	*Ways to verify and compare theory and experimental results finding theoretical support understanding the relationship between physics and computational modeling*

> *"Because when working on a long-term research project you independently study the theory and the physical terms related to your phenomenon."*

The findings thus reveal an incompatibility between the way experts perceive the theoretical aspect of research; i.e., the development of a theoretical model [49], and the students' perception of the theoretical aspect. The students' components dealt with comparing the results of the experiment with existing results or formulas, without actively constructing a model (by considering simplification assumptions or refining the model to achieve agreement with measurement). The only exception was the component development of equations and formulas that depicts a constructive aspect of theoretical work.

In terms of the practice defining and focusing research question, no group identified it as a distinct category, and students did not refer to this category in the individual questionnaires.

Although these practices are more applicable to long-term experimental work because they enable processes of refinement of the research topic as well as constructing and revising a theoretical model to fit experimental model, this finding is important since the development team indeed sought to engage the students to some extent in these practices during the foundation stage.

As described in the context section, the development team chose to focus at the beginning of the introductory stage on the phenomenological aspect of research and introduce the construction of the theoretical model only towards the end of the introductory stage via computational modeling activities. This was done to allow the students to investigate a wide range of phenomena and not be limited to phenomena that can be analyzed with their (relatively weak) scientific and mathematical knowledge. Also, for students who usually focus on the theoretical aspects of physics in their home school courses it was important to emphasize the experimental component of the physical research process.

The findings show that the separate introduction of the role of the theoretical model led to a misconception in that the students maintained their previous view that scientific research is mainly phenomenological and did not identify theoretical work as central to the research process.

C. Teamwork and communication of knowledge

The findings on students' views of these two practices were surprising. Students recognized their centrality in the introductory activities (as intended by the designers), yet did not value their early engagement in these practices as fruitful for later project work.

Students viewed teamwork and communication of knowledge as central practices in the introductory stage of the RP program: all teams' lists included inquiry components that corresponded to these categories, and most groups recognized them as distinct categories (5/8 groups for communication of knowledge, 6/8 for "teamwork"). Table IV lists the different labels that the groups gave to the teamwork category, as well as examples of the inquiry components that they included:

The students identified several elements that make up successful teamwork: collaboration, division of labor and communication. It is also apparent that the students linked teamwork mainly with the challenges associated with it such as working with unfamiliar partners, lack of cooperation or communication problems.

Only ∼25% of students in the groups that identified the categories of teamwork and communication of knowledge supported the introduction of these practices in the introductory stage. About a third were against (for comparison, none of the students were opposed to introducing categories 1–4) and the rest did not mention these practices in their individual responses. Students gave two types of explanations for their negative evaluation:

1. Reasons related to the value of these practices in the context of short-term activities:

(a) Teamwork is not effective in the context of short-term inquiry, the advantages of teamwork only become clear in long-term cooperation: *"If the investigation is short cooperation in the group cannot lead to optimal results."*

(b) Sharing knowledge is pointless if one cannot formulate sound scientific explanations: *"When working on*

TABLE IV. Student categories corresponding to the top-down category "teamwork" and examples for components included in them.

Group number	Category name	Example of components included in category
1	*Communication*	*Communication between group members* *Communication with teachers* *Effective teamwork*
2	*Human challenges*	*Communication problems* *Working with new people* *Presenting in front of people*
4	*Working or learning in a team*	*Teamwork* *Expressing oneself in a group* *Division of labor*
5	*Working in a group*	*Working in pairs* *Collaboration*
7	*Working in a group*	*Giving and receiving criticism* *Division of labor* *Dealing with teamwork*
8	*Collaboration in a group*	*Working with students I don't know* *Cooperative group learning* *Seeking help from others*

short-term projects theoretical knowledge is not sufficiently established, so sharing it is unnecessary or not clear enough."

"Only in a long project we reach a deep understanding of the subject that requires sharing and documentation."

2. Reasons related to the irrelevance of these practices to the nature of scientific research:

(a) Teamwork (especially overcoming communication difficulties) is not inherent to scientific research: *"In my opinion working in a group is not really important in research. It is a social tool that is intended to make research easier but is not really important to the research itself."*

"Collaboration in the group—in my opinion this is the least necessary—that is, studies can be carried out either alone or in a familiar and safe environment."

(b) Communicating knowledge is not an integral part of the research process but rather a technical necessity: *"After conducting research and producing results, sharing of knowledge is important, but it is not a central part of the process. It is more technical."*

These findings contrast sharply with the design of the introductory stage, which required teamwork on every activity and provided students with feedback on their writing and presentation skills.

VI. SUMMARY AND DISCUSSION

This study aims to contribute to the design of learning progressions in inquiry across different experimental settings. The GAIQ ([56]) served as a data collection tool that encouraged students to reflect on their learning experience and explicate their attitudes towards the value of inquiry practices they experienced in the introductory stage to their later work on extended research projects. The analysis compared top-down categories of inquiry practices with those that students defined as tasks they had to cope with during the introductory stage and described students' views with respect to these categories.

Figure 2 provides an overview of the findings: The correspondence between the top-down and student-made categories, as well as students' attitudes towards their engagement in the different categories during the introductory stage.

Many of the top-down categories matched the student categories. Most of the students in the groups that identified the categories constructing an experimental setup, selecting and operating research tools, data analysis, and self-monitoring also claimed that these practices should be part of the introductory stage activities because they are relevant to their extended project work.

Of special interest are the categories teamwork and communication of knowledge, both of which represent aspects of engagement in the scientific community. Although these categories were identified by most groups as central in the introductory stage, they were not perceived as fruitful for later engagement in research projects. This finding contrasts with the introductory stage emphasis on teamwork and the constant feedback on students' writing and presentation skills.

These findings suggest that students appreciated the structured design of the introductory stage activities for some of the experimental research practices (i.e., constructing an experimental setup, selecting and operating measurement tools, data analysis and self-monitoring of work), but did not recognize the relevance of the instructional design for practices related to engagement in the scientific community.

These results can be interpreted within the framework of boundary crossing [15], which makes it clear that learning authentic scientific practices is not a linear, incremental learning process, but rather a process of enculturation: understanding and overcoming differences in norms and perceptions between two cultures [57]. Students, who are grounded in their school culture, are required to adhere to the norms and practices of a different culture, i.e., that of the experimental physics laboratory.

The learning sequence was successful for practices that had the same meaning across the two cultures, such as

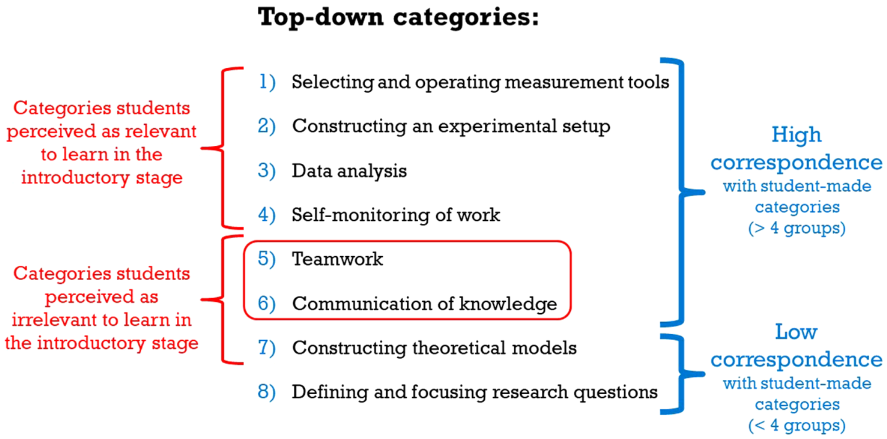

FIG. 2. Overview of findings: correspondence between student-made and top-down categories and perceived relevance of each category.

using research tools, data analysis or self-regulation, although these practices differ in terms of the sub-practices they involve in the different settings. Nevertheless, the shared meaning allows for the development of a learning progression for these practices, increasing in complexity from novice to expert levels.

On the other hand, practices related to engagement in the scientific community have fundamentally different meanings in the two cultures and were therefore less likely to be transferable. These practices were reflected in different ways at the different stages of the program, so students considered them irrelevant to transfer from one to the other.

A good example is teamwork. In the traditional instructional lab, teamwork translates into a process in which all team members carry out similar tasks simultaneously to develop similar conceptual knowledge. In a research laboratory, researchers divide the work so that each investigates a different aspect of a problem, and then share their results to create a common product. The same term conveys different meanings: In the instructional lab, teamwork signifies performing a similar task to arrive at a known result, while in the research lab it refers to performing different tasks to generate a new result.

The two cultures also differ with respect to the communication of knowledge. In the scientific culture, the reputation of a researcher and the sustainability of their research are determined by peer reviews. Therefore, communication of knowledge is vital and takes the form of a scientific debate which involves presenting an argument, defending it, and criticizing the arguments of others. In school culture, presentations commonly serve to sum up students' work in a festive way and to practice speaking in front of an audience. Presentations are viewed as a safe, nonintimidating experience with minimal judgment (since the speaker's peers are not in charge of assessment).

Although teamwork and communication of knowledge were defined as learning objectives in the RP program, they were reflected differently in the two stages of the program. The authentic characteristics of teamwork and scientific communication were not imported by the design team into the introductory stage. Our findings indicate that students' perceptions of these practices reflected their school culture and were therefore perceived as ineffective in preparing them for their extended research projects. It is important to note that some students still hold these "school" views when referring to their project work (e.g., the views that research can be done alone, or that presenting research is not an integral part of the process). This can be explained by the fact that students were at the beginning of their projects and only towards the end of their work did they experience some of the authentic features of scientific research, such as presenting and defending their work in front of an external examiner to receive their final assessment.

As stated in the literature review (Sec. I), studies on students' views in introductory labs using the E-CLASS questionnaire [22–25] reveal a gap between students' perceptions of the nature of experimental physics and expert-like perceptions. The findings of this study reinforce the existence of this gap and provide some further examples.

As Wilcox and Lewandowski [24] have shown, inquiry-oriented labs and project-based courses that engage students in broader aspects of research have a positive impact on their perceptions of the nature of experimental physics. The E-CLASS questionnaire addresses social aspects of experimental research in 2 out of its' 30 items—the aspects of teamwork and communication of knowledge. This study extends the investigation of students' perceptions of these social aspects of research.

Our findings strongly resonate with those reported by Stanley and Lewandowski [34] regarding scientific communication. They showed that students who wrote lab journals during their undergraduate labs indicated that this experience did not serve them in their advanced research because there was no genuine need to keep a journal to document short, structured activities. The boundary crossing lens suggests that the features of authentic scientific documentation were not reflected in the undergraduate lab, so the two settings differed in the meaning they attributed to documentation. This presented a boundary for students who wanted to draw on their prior experiences.

The results of our study and the studies cited above suggest that these social aspects, i.e., changes in the "rules of the game," should be made explicit in the design of laboratory settings that attempt to bridge the gap between school culture and scientific research culture.

When designing a learning sequence in inquiry across different experimental settings, caution should be exercised when introducing practices that have different meanings in school and scientific culture. Designers should seek to reflect the authentic features of scientific research in the early stages of learning. In this way, students can gradually develop as researchers and cross the cultural boundaries between their school and the experimental lab.

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APPENDIX: SEMISTRUCTURED ACTIVITIES OF THE RP INTRODUCTORY STAGE

Table V provides examples of the instructional design of the introductory stage that illustrate the use of the mechanisms of structuring and problematizing [46].

TABLE V. Description of instructional design—examples of problematizing and structuring of activities in the RP introductory stage.

Phenomena	Motion of cupcake cups in the air	Determining the speed of light from astronomical measurements (Rømer's experiment)	Dependence of a spring's stiffness on variables (e.g., length, temperature) and in systems (e.g., static, oscillating) chosen by the students.
Duration	4 h	10 h	8 h
Learning goals	• Considerations in experimental design (controlling variables, precision of measurement tools) • Proper use of measurement and analysis tools (e.g., video camera, Tracker). • Construction of scientific argument: characterizing a motion based on empirical evidence. • Knowledge sharing practices: Communication of scientific argument in written reports	• Distributing work in a team to process and analyze a vast database. • Reconstruction of a measurement method described in a scientific report in a popular manner. • Identifying patterns in data	• Identifying and articulating research questions with regard to systems (mass on a spring) presented by the teacher. • Designing an investigation (controlling variables, considering precision of measurement tools) • Communication of scientific argument in oral and written reports
Sample instructional scaffolds	Problematizing: Proper use of measurement tools: Students were asked to compare videos of a falling object, identify drawbacks affecting the validity of the investigation and devise considerations for optimal video documentation. Structuring: knowledge sharing practices: students were required to follow a prescribed framework in their lab reports.	Structuring: Collaboration in producing and analyzing a vast dataset: pairs of students were assigned sections of the phenomenon of interest and followed a similar measurement procedure that was assimilated via a pre-prepared template to produce a collaborative dataset. Problematizing: Data analysis: students were required to devise a representation of Io's orbit—identifying a pattern in the assimilated data while considering measurement errors (i.e., systematic fluctuations in orbit period).	Structuring: Formulation of research question: students were asked to formulate research questions related to the traditional Hooke's law lab setup (that they were already acquainted with) following a defined structure (e.g., dependence between two variables such as a spring's stiffness (K) and temperature) Problematizing: Focusing research: students were asked to come up with criteria to guide their selection of questions for investigation (e.g., compatibility with defined structure, feasibility given lab constraints, interest, plausibility given theoretical considerations, etc.)

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