



## VIRTUAL PRACTICAL WORK FOR QUALITY LEARNING IN LIFE AND EARTH SCIENCES: STUDENT PERFORMANCE AND PERCEPTIONS

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### ABSTRACT

Although virtual laboratories are increasingly used to address constraints on practical science learning, evidence remains limited on locally developed virtual laboratories in Moroccan lower-secondary science and on evaluations that combine objective conceptual and procedural learning outcomes with multidimensional learner perceptions. This study compared students' conceptual and procedural knowledge after using LabInnov or receiving conventional non-laboratory instruction and examined users' perceptions of the platform. A quantitative exploratory quasi-experimental study used a post-test-only non-equivalent-group design with 34 third-year lower-secondary students from two intact classes, with one class assigned to each instructional condition. The experimental group ( $n = 17$ ) used LabInnov during two 120-minute sessions, while the control group ( $n = 17$ ) studied the same scientific content conventionally. Both groups completed a ten-item post-test scored from 0 to 20, and the experimental group completed a 15-item questionnaire assessing satisfaction, usability, perceived understanding, motivation, and collaboration. The experimental group achieved higher post-test scores ( $M = 13.06$ ,  $SD = 2.34$ ) than the control group ( $M = 9.06$ ,  $SD = 2.04$ ), with a mean difference of 4.00 points, 95% CI [2.47, 5.53],  $t(32) = 5.318$ ,  $p < .001$ , with a large effect ( $d = 1.82$ ). Questionnaire means ranged from 3.65 to 4.67, and motivation was positively associated with perceived understanding (Spearman's  $\rho = .631$ ,  $p = .006$ ). These findings suggest that LabInnov may support conceptual and procedural knowledge when regular practical work is constrained. However, the small sample, post-test-only design, and use of only one intact class per condition prevent causal attribution and leave open the possibility that the observed difference partly reflects class-level characteristics. Conceptually, the study contributes an integrated evaluative perspective on virtual laboratory learning by considering objective conceptual and procedural outcomes alongside multidimensional learner perceptions and the relationship between motivation and perceived understanding within a locally developed Moroccan virtual laboratory context.

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Keywords: practical work; virtual laboratory; conceptual and procedural knowledge; motivation; secondary education

### INTRODUCTION

Achieving inclusive and equitable quality education, as promoted by Sustainable Development Goal 4 (SDG 4), requires learning conditions that enable students not only to acquire

scientific knowledge but also to investigate phenomena, interpret evidence, and develop relevant digital competencies (Vuorikari et al., 2022). The UNESCO Global Education Monitoring Report indicates that technology is explicitly involved in six of the ten SDG 4 targets and may contribute to educational access, equity, quality, skills development, and system management (UNESCO,

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2023). Nevertheless, technology's educational value is not automatic; it depends on accessibility, pedagogical relevance, sustainability, and integration into coherent teaching practices. In science education, this issue matters because understanding scientific concepts is closely connected to opportunities for observation, experimentation, and interpretation.

The need to strengthen science learning is particularly evident in the Moroccan context. According to the 2022 Program for International Student Assessment, only 25% of Moroccan students attained at least Level 2 proficiency in science, compared with an average of 76% across OECD countries (OECD, 2023). These international findings are complemented by previous research documenting the challenges associated with ICT integration in Moroccan Life and Earth Sciences education (Nafidi et al., 2018) and by empirical evidence collected in the Moroccan school context. In a preliminary study of 720 Life and Earth Sciences teachers and 575 secondary school students, nearly 60% of teachers reported that they rarely organized practical work sessions. Technical constraints, including insufficient equipment and expired materials, were reported by 84% of the teachers, while 66.2% identified oversized classes as an additional obstacle (Jebara et al., 2025a). These results provide an empirical basis for investigating context-appropriate digital environments that can expand students' access to experimental learning opportunities.

Practical work is an essential component of science education because it helps students connect scientific concepts with procedures, observations, and evidence (Najoui & Alami, 2017; Oliveira & Bonito, 2023). However, its regular implementation may be restricted by insufficient equipment, limited instructional time, large classes, and other logistical constraints, including those documented in Moroccan secondary education (Akuma & Callaghan, 2019). Virtual laboratories can complement practical science activities when access to physical laboratories is limited, offering students opportunities to engage with simulated experimental tasks under reduced material constraints (Fadda et al., 2022; Shambare & Simuja, 2022). Their educational value and adoption nevertheless depend on interactivity, platform effectiveness, and appropriate instructional design (Achuthan et al., 2021; Chan et al., 2021; Radhamani et al., 2021). Meta-analytic evidence further indicates that digital tools and computer simulations can support science learning, particularly when integrated with other instructional approaches rather than used as sub-

stitutes (Hillmayr et al., 2020). A second-order systematic review of virtual and remote laboratories in secondary STEM education found that online laboratories generally supported learning outcomes comparable to those in physical laboratories, particularly when integrated into conventional instruction and accompanied by appropriate teacher feedback (Fadda et al., 2022). At the same time, adding immersive features does not automatically improve learning, because increased presence may bring additional cognitive demands (Makransky et al., 2019). The same review nevertheless showed that content knowledge remained the most frequently assessed outcome, whereas practical skills, inquiry processes, and variables related to students' learning experiences were examined less consistently. Recent studies also emphasize designing virtual laboratories and digital learning platforms around accessibility, sustainability, disciplinary alignment, and adaptable learning scenarios (El Kharki et al., 2021; Shchevliagin & Koroleva, 2024; Zhang & Liu, 2024).

Recent empirical studies illustrate both the potential of digital simulations and the remaining research gaps. Ahmad et al. (2021) examined an interactive computer animation and simulation module for learning electrochemistry through a quasi-experimental design focusing on achievement and motivation. Their findings supported the educational value of interactive simulations, but the investigation was limited to a specific chemistry topic and did not examine a broader profile of usability, satisfaction, perceived understanding, and collaboration. Similarly, Widiyatmoko et al. (2023) found that virtual reality game-based learning improved eighth-grade students' STEM literacy. However, their study focused on energy concepts and did not examine virtual practical work in Life and Earth Sciences or a multidimensional profile of students' perceptions. Taken together, these studies reveal a specific research gap: classroom-based evidence remains limited on locally developed virtual practical-work environments in Moroccan lower-secondary Life and Earth Sciences that combine objective assessment of conceptual and procedural knowledge with a multidimensional examination of students' perceptions. Previous research has examined motivation, experiences, and attitudes in virtual laboratory settings (Dyrberg et al., 2017; Diwakar et al., 2023; Kapici et al., 2020), but these outcomes have rarely been examined alongside objective knowledge outcomes within the same classroom investigation.

Against this background, LabInnov was developed as an interactive platform designed to support virtual practical work across different topics in Life and Earth Sciences. Previous research focused on the platform's instructional design, technological development, pedagogical scripting, and initial evaluation following the ADDIE model (Jebara et al., 2025b). Initial user feedback indicated favorable perceptions of its usability, interactivity, and pedagogical potential, while also identifying areas for improvement, including cross-device compatibility and expanding available experimental content. The present research moves from platform design and initial evaluation to a comparative pilot investigation in an authentic lower-secondary classroom setting. The experimental identification of food constituents is the activity selected for this classroom evaluation, not the only scientific content for which LabInnov was designed. The five perception dimensions were treated as complementary indicators of students' experience rather than as components of a single theoretical model. Self-Determination Theory informed motivation, interface usability by the Technology Acceptance Model, and social interaction and collaboration by Moore's learner-learner interaction framework, whereas satisfaction and perceived understanding were treated as exploratory indicators of affective experience and subjective learning, respectively (Davis, 1989; Moore, 1989; Ryan & Deci, 2020). The association between motivation and perceived understanding was of particular theoretical interest because Self-Determination Theory links motivation to engagement and sustained learning effort, making its relationship with students' subjective appraisal of their understanding theoretically relevant (Ryan & Deci, 2020).

This study's novelty lies in its context-sensitive pilot evaluation of a locally developed virtual practical-work platform in Moroccan lower-secondary Life and Earth Sciences, using complementary evaluation perspectives. Specifically, the study combines an objective comparison of conceptual and procedural knowledge with a five-dimensional examination of students' perceptions and an exploratory analysis of associations among these perceptions. Importantly, the comparison is between LabInnov and conventional non-laboratory instruction; the control condition did not involve physical laboratory work or a teacher demonstration of the experiment. Accordingly, the study does not evaluate whether virtual laboratories are superior to physical laboratory activities.

This study aims to support and extend previous findings concerning the educational potential of virtual laboratories. More specifically, it aims to: (1) compare the post-test conceptual and procedural knowledge scores of students using LabInnov with those of students receiving conventional non-laboratory instruction; (2) quantify the levels of satisfaction, interface usability, perceived understanding, motivation, and social interaction and collaboration reported by LabInnov users; and (3) examine the associations among these five perception dimensions using Spearman's rank correlations.

Accordingly, the study addresses the following research questions:

RQ1. Do the post-test conceptual and procedural knowledge scores of students who use LabInnov differ from those of students receiving conventional non-laboratory instruction on the same scientific content?

RQ2. What levels of satisfaction, interface usability, perceived understanding, motivation, and social interaction and collaboration do students report after using LabInnov?

RQ3. What associations exist among these five perception dimensions, with particular attention to the theoretically motivated association between motivation and perceived understanding?

This study is positioned as a pilot investigation of a locally developed virtual laboratory in lower-secondary Life and Earth Sciences. Its findings are intended to provide preliminary evidence on students' performance and perceptions rather than establish the general superiority of virtual laboratories or broadly generalizable causal effects.

## METHODS

This study is part of a progressive research program devoted to developing and evaluating LabInnov. Previous work focused on the platform's instructional design, technological development, pedagogical scripting, and initial evaluation following the ADDIE model (Jebara et al., 2025b). The present study therefore represents the next stage of this research process, moving from platform development and initial evaluation to a first comparative investigation under authentic classroom conditions. It was designed as a pilot study involving two intact classes from a single school, comprising 34 students. The limited sample size aligned with the exploratory purpose of this stage, which aimed to gather preliminary evidence on students' performance and user experience before conducting larger-scale investigations. Accordingly, the sample was not intended

to represent the broader secondary-school population, and the findings should be interpreted as preliminary evidence to inform subsequent studies with larger and more diverse samples.

Guided by established and contemporary principles of quasi-experimental research (Reichardt, 2019; Shadish et al., 2002), the study was organized into five researcher-defined stages: (1) inclusion of the two pre-existing intact classes and establishment of the two instructional conditions; (2) development and content review of the research instruments; (3) implementation of the experimental and conventional learning activities; (4) administration of the knowledge post-test and perception questionnaire; and (5) quantitative data processing, analysis, and interpretation. Within this methodological framework, the procedure was adapted to the school's organizational constraints by retaining intact classes, omitting individual randomization, and using a post-test-only design. These adaptations preserved the school's usual organization while allowing comparison of the two instructional conditions under structured conditions.

The participants were 34 third-year lower-secondary students enrolled in a private school in Casablanca, Morocco. They belonged to the two pre-existing third-year lower-secondary classes available in the participating school and followed the same Life and Earth Sciences curriculum. The school administration formed these classes at the beginning of the academic year, before the study was planned, as part of the school's usual organization. According to the school's administrative practice, class composition was intended to maintain broadly balanced groups. Because the classes followed fixed timetables and could not be reorganized for research purposes, students were neither reassigned nor mixed across classes. The study therefore involved both intact classes, and the sample size reflected the accessible population rather than an *a priori* power-based determination (Lakens, 2022). One class formed the experimental group ( $n = 17$ ), while the other formed the control group ( $n = 17$ ). The designation of the two intact classes as experimental or control was pragmatic and followed the order of the scheduled sessions: the class taught in the first session was designated as the experimental group, whereas the other served as the control group. No random procedure assigned classes to the two instructional conditions. Assignment consequently occurred at the class level without individual randomization. Administrative efforts to balance class composition should not be interpreted as evidence of statistical baseline

equivalence between the two groups. Because instructional condition coincided with class membership, observations within each class may not have been fully independent. With only one intact class per condition, intra-class correlation and class-specific effects could not be estimated separately from the instructional-condition effect; we therefore considered this limitation when interpreting the between-group comparison.

The school administration authorized the study. The collected data were anonymized and used exclusively for research purposes. Participation in the study had no consequences for students' school grades.

The intervention took place over two 120-minute sessions, for a total of 240 minutes, and focused on the experimental identification of food constituents. At the beginning of the first session, the teacher presented the learning objectives and general instructions. The experimental group then began the virtual practical activities using LabInnov in a multimedia room equipped with individual computers. Students selected virtual equipment and reagents, followed the experimental protocols, and observed simulated reactions used to identify different food constituents.

During the same period, the control group studied the same scientific content using textual materials and teacher explanations, without using a virtual laboratory or conducting physical experimental manipulations. This condition reflected the constraints observed in various Moroccan schools, where insufficient or unavailable laboratory equipment can limit the regular implementation of practical activities in Life and Earth Sciences (Jebara et al., 2025a). The second session continued and completed the learning activities in both groups. The scientific content, learning objectives, overall instructional duration, and teacher were kept comparable across the two conditions. The main difference concerned the learning modality and instructional resources used. Both groups were supervised by their regular teacher to limit variation from teacher change and maintain a familiar learning environment.

At the end of the second session, all 34 students completed the same knowledge post-test under identical instructions. Students were given 20 minutes to complete the post-test. Immediately afterward, the 17 students in the experimental group completed a questionnaire concerning their experience with LabInnov. No missing data were observed. Consequently, all 34 post-tests and all 17 questionnaires were included in the statistical analyses.

Two quantitative instruments were used: a criterion-referenced knowledge post-test administered to both groups and a perception questionnaire administered only to the experimental group. The post-test comprised ten multiple-choice questions assessing conceptual and procedural knowledge related to the experimental

identification of food constituents. Each question had one correct answer. Correct answers were awarded two points, while incorrect or unanswered responses received zero points, resulting in a total score ranging from 0 to 20. Table 1 presents the post-test structure.

**Table 1.** Structure of the Conceptual and Procedural Knowledge Post-Test

| Assessed domain                                                 | Items  | Number of items | Maximum score |
|-----------------------------------------------------------------|--------|-----------------|---------------|
| Purpose of the practical activity and functions of the reagents | Q1-Q2  | 2               | 4             |
| Food constituents, reagents, and expected results               | Q3-Q7  | 5               | 10            |
| Equipment, procedures, and hygiene rules                        | Q8-Q10 | 3               | 6             |
| Total                                                           | Q1-Q10 | 10              | 20            |

Three teachers specializing in Life and Earth Sciences qualitatively examined the post-test content validity, following the general principles of expert-based content validation described by Lynn (1986). The experts examined the scientific relevance, clarity, and alignment of each item with the intended learning objectives. Their observations resulted in minor wording revisions before the instrument was administered. The total score indicated students' conceptual and procedural knowledge related to this specific learning activity rather than their overall experimental competence.

The post-activity questionnaire comprised 15 items organized into five dimensions of three items each: general satisfaction, interface usability, perceived understanding, motivation to participate, and social interaction and collaboration. Responses were recorded on a five-point Likert-type scale ranging from 1, "strongly disagree," to 5, "strongly agree" (Likert, 1932; Jebb et al., 2021). A score was calculated for each dimension by averaging responses to its three corresponding items. Dimension scores therefore ranged from 1 to 5, with higher values representing more positive perceptions.

The researchers developed the questionnaire items using complementary theoretical frameworks and adapted them to the students' age, the virtual practical-work setting, and the functions of LabInnov. They were not direct reproductions of standardized scales. Items addressing motivation and interest in the activity were informed by Self-Determination Theory (Ryan & Deci, 2000, 2020) and recent work on measuring student engagement (Fredricks et al., 2019). Perceived interface usability was informed by the Technology Acceptance Model (Davis, 1989). Items addressing exchanges, peer support, and collaboration were linked to learner-learner

interaction in Moore's (1989) interaction framework. General satisfaction and perceived understanding were treated as exploratory indicators of students' experiences. Perceived understanding represented students' subjective assessment of the extent to which LabInnov supported their understanding of the scientific content and was therefore distinguished from the objective performance assessed by the post-test.

Three experts qualitatively examined the questionnaire's content validity: two specialists in Life and Earth Sciences education and one specialist in educational psychology. Following the principles of expert judgment described by Lynn (1986), they examined the relevance, clarity, and correspondence of the items with their intended dimensions. Their feedback led to minor wording adjustments before administration. Because the questionnaire was developed specifically for this exploratory study, the internal consistency of each three-item dimension was subsequently examined using Cronbach's alpha (Cronbach, 1951; Taber, 2018). Taken together, the expert review and internal-consistency analyses provided preliminary evidence regarding content validity and internal consistency. Given the small number of experts, the limited sample of 17 respondents, and the three-item structure of each dimension, these results should not be interpreted as constituting a full psychometric validation of the questionnaire.

The statistical analyses were conducted using R version 4.5.0 within RStudio version 2024.12.1+563 (Posit Team, 2025). Means, medians, standard deviations, first and third quartiles, and minimum and maximum values were calculated to summarize post-test performance and questionnaire dimension scores. Frequency histograms also displayed the distribution of post-test scores in each group.

Before comparing post-test means, the assumptions underlying the independent-samples Student's *t*-test were examined. The Shapiro-Wilk test (Shapiro & Wilk, 1965) and visual inspection of the distributions were used to assess the normality of post-test scores in each group. Homogeneity of variance was examined using Levene's test (Levene, 1960). Because the normality and homogeneity assumptions were met, the mean post-test scores between the experimental and control groups were compared using an independent-samples Student's *t*-test (Student, 1908). The mean difference was reported with its 95% confidence interval.

Cohen's *d* and its small-sample bias-corrected estimate, Hedges' *g*, were calculated to quantify the magnitude of the between-group difference (Hedges, 1981; Cohen, 1988). These foundational effect-size measures were interpreted alongside confidence intervals and statistical significance, following more recent recommendations emphasizing contextual and cautious interpretation of effect magnitude (Funder & Ozer, 2019).

The internal consistency of each questionnaire dimension was evaluated separately using Cronbach's alpha. Descriptive statistics were then calculated for each of the five dimensions. Spearman's rank correlation coefficients were used to

examine associations among general satisfaction, interface usability, perceived understanding, motivation, and collaboration (Spearman, 1904; Schober et al., 2018). Spearman's coefficient was selected because the dimension scores were derived from Likert-type responses and because of the small sample size. The relationship between motivation and perceived understanding constituted the main theoretically relevant association, while the remaining correlations were treated as exploratory. All inferential tests were two-sided, and the statistical significance threshold was .05. Given the small sample, we interpreted questionnaire-based associations cautiously and did not treat them as evidence of causal or predictive relationships. No multivariable regression analysis was retained because the experimental-group sample was too small to provide stable estimates for a model with several predictors.

## RESULTS AND DISCUSSION

The analysis addressed the two components of the research problem: the difference in post-test performance between the experimental and control groups and the perceptions reported by students who used LabInnov. Table 2 presents the descriptive statistics for the conceptual and procedural knowledge post-test.

**Table 2.** Post-Test Scores of the Experimental and Control Groups

| Group              | n  | Mean  | SD   | Minimum-maximum |
|--------------------|----|-------|------|-----------------|
| Experimental group | 17 | 13.06 | 2.34 | 10.00-17.00     |
| Control group      | 17 | 9.06  | 2.04 | 6.00-13.00      |

The experimental group obtained a mean score of 13.06 (SD = 2.34), compared with 9.06 (SD = 2.04) for the control group. The observed mean difference was therefore 4.00 points in favor of the experimental group. The median score was also higher in the experimental group (13.00) than in the control group (9.00), while the interquartile ranges and minimum-maximum values showed a general shift toward higher scores among students who used LabInnov. Before comparing the means, the assumptions of the

independent-samples Student's *t*-test were examined. The Shapiro-Wilk tests were not statistically significant in either group, providing no evidence against the normality assumption. Levene's test was also not statistically significant ( $p = .454$ ), indicating no evidence of unequal variances. The conditions for applying the independent-samples Student's *t*-test were therefore considered acceptable. Table 3 presents the inferential comparison and effect-size estimates.

**Table 3.** Comparison of Post-Test Scores Between the Experimental and Control Groups

| Analysis                | Statistic | df    | p       | Mean difference | Standard error | 95% CI       | Effect size          |
|-------------------------|-----------|-------|---------|-----------------|----------------|--------------|----------------------|
| Levene's test           | F = 0.576 | 1, 32 | 0.454   | —               | —              | —            | —                    |
| Student's <i>t</i> test | t = 5.318 | 32    | < 0.001 | 4.00            | 0.752          | [2.47, 5.53] | d = 1.82<br>g = 1.78 |

The two-sided independent-samples Student's *t*-test indicated a statistically significant difference between the two classes,  $t(32) = 5.318$ ,  $p < .001$ . The observed mean difference was 4.00 points, with a 95% confidence interval ranging from 2.47 to 5.53 points. The standardized difference was large according to both Cohen's *d* (1.82) and the small-sample-corrected Hedges' *g* (1.78). However, these effect-size estimates should be interpreted cautiously. The result represents an observed between-class difference, with the class using LabInnov showing higher post-test concep-

tual and procedural knowledge scores than the class receiving conventional non-laboratory instruction. Because no baseline measure was available and only one intact class represented each instructional condition, the observed difference cannot be separated from possible pre-existing class-level differences and should not be interpreted as a causal effect of LabInnov.

Before examining students' perceptions, the internal consistency of the five questionnaire dimensions was assessed. Table 4 presents the coefficients.

**Table 4.** Internal Consistency of the Perception Questionnaire Dimensions

| Dimension               | Number of items | Cronbach's alpha |
|-------------------------|-----------------|------------------|
| General satisfaction    | 3               | .810             |
| Interface usability     | 3               | .767             |
| Perceived understanding | 3               | .789             |
| Motivation              | 3               | .800             |
| Collaboration           | 3               | .810             |

Cronbach's alpha coefficients ranged from .767 to .810. General satisfaction and collaboration produced the highest coefficients, followed by motivation, perceived understanding, and interface usability. These values provided preliminary evidence of acceptable internal consistency for the five dimensions. Nevertheless, they should

be interpreted cautiously because each coefficient was calculated from only three items and 17 respondents.

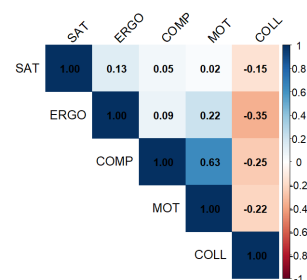
Table 5 presents the descriptive results for the five questionnaire dimensions. All scores were calculated on a scale ranging from 1 to 5.

**Table 5.** Descriptive Statistics for the Perception Questionnaire Dimensions

| Dimension               | n  | Mean | SD   | Median | Minimum | Maximum |
|-------------------------|----|------|------|--------|---------|---------|
| General satisfaction    | 17 | 3.65 | 0.55 | 4.00   | 2.00    | 4.00    |
| Interface usability     | 17 | 4.45 | 0.66 | 5.00   | 3.33    | 5.00    |
| Perceived understanding | 17 | 4.67 | 0.47 | 5.00   | 3.33    | 5.00    |
| Motivation              | 17 | 4.33 | 0.63 | 4.00   | 3.00    | 5.00    |
| Collaboration           | 17 | 4.51 | 0.55 | 5.00   | 3.67    | 5.00    |

Perceived understanding received the highest evaluation ( $M = 4.67$ ,  $SD = 0.47$ ), followed by collaboration ( $M = 4.51$ ,  $SD = 0.55$ ), interface usability ( $M = 4.45$ ,  $SD = 0.66$ ), and motivation ( $M = 4.33$ ,  $SD = 0.63$ ). General satisfaction was more moderate ( $M = 3.65$ ,  $SD = 0.55$ ) but remained above the response scale midpoint. Median scores reached 5.00 for perceived understanding, interface usability, and collaboration, indicating that responses for these dimensions were concentrated toward the upper end of the scale.

Spearman's rank correlations were calculated to examine the associations among the five questionnaire dimensions. Figure 1 presents the coefficients.



**Figure 1.** Heatmap of Spearman's Rank Correlations Among the Perception Questionnaire Dimensions

(Note. SAT = general satisfaction; ERGO = interface usability; COMP = perceived understanding; MOT = motivation; COLL = collaboration. Blue cells indicate positive correlations, whereas red cells indicate negative correlations. The COMP-MOT correlation was statistically significant ( $p = .631$ ,  $p = .006$ ); all other correlations were not statistically significant.)

Most associations were weak and not statistically significant. The theoretically relevant relationship between motivation and perceived understanding was positive and statistically significant ( $\rho = .631$ ,  $p = .006$ ). Students reporting greater motivation therefore tended to report stronger perceived understanding. The remaining coefficients ranged from  $-.350$  (between interface usability and collaboration) to  $.217$  (between interface usability and motivation) and were not statistically significant. Because several dimensions had high median scores and limited variability, the absence of significant correlations should not be interpreted as evidence that the constructs were entirely unrelated.

The observed post-test difference may be discussed in light of the learning opportunities provided by the virtual environment, although the mechanisms underlying this difference were not directly tested in the present study. LabInnov required students to select equipment and reagents, follow an experimental sequence, and connect each simulated reaction with an expected observation. These features may have made the activity's procedural organization more explicit than in the text-and-explanation condition. More generally, previous research suggests that virtual laboratories can make processes visible, allow learners to control variables, and provide immediate representations of experimental outcomes. Al-Duhani et al. (2023), for example, reported higher achievement among Grade 8 students using a virtual laboratory for electricity and discussed visualization, variable control, and immediate feedback as possible explanatory features. In the present study, however, these mechanisms should be regarded as plausible interpretations rather than empirically tested mediators of the observed between-class difference.

The present pattern is also consistent with evidence that structured virtual and blended laboratory activities can support conceptual knowledge, inquiry learning, scientific literacy, and argumentation skills (Kapici et al., 2019; Agustina & Putra, 2022; Lestari et al., 2023; Muilwijk & Lazonder, 2023), while their benefits remain dependent on pedagogical guidance and appropriate instructional structure (Kapici et al., 2022). However, the current comparison differed in an important respect: the control group did not have access to either a physical laboratory or a teacher demonstration of the experiment. The higher scores should therefore be interpreted as evidence that LabInnov offered experimental representations and procedural learning opportunities that were absent from the conventional condi-

tion, rather than as evidence that it was superior to physical laboratory work. This interpretation aligns with recent evidence showing that physical and virtual experiments offer complementary affordances and that combining both formats can support conceptual understanding in science learning (Wörner et al., 2022; Sarapak et al., 2025). This distinction matters because the post-test assessed knowledge of equipment, reagents, observations, and procedures but not students' ability to manipulate physical materials.

The particularly high perceived-understanding score was observed alongside higher post-test performance in the experimental class, although the two measures represent different constructs and were not directly analyzed in relation to one another. The post-test assessed demonstrated knowledge, whereas perceived understanding reflected students' subjective judgment of how much the platform helped them understand. Distrik et al. (2024) similarly found that an interactive digital resource incorporating visual materials supported high-school students' conceptual understanding, digital literacy, and positive learning responses. In the present study, the objective post-test results and the perceived-understanding scores should therefore be considered complementary indicators of students' learning experience rather than evidence of a direct convergence between objective and subjective measures.

High usability did not produce an equally high general-satisfaction score. This difference suggests that ease of interaction with the platform was only one component of students' overall experience. General satisfaction may also depend on expectations, preference for physical manipulation, novelty, visual design, or occasional technical constraints. Viitaharju et al. (2023) emphasized that an effective virtual laboratory experience depends on aligning relevant scientific content, learning design, and technical feasibility. Because the present study did not include qualitative interviews, the reasons for the more moderate satisfaction score cannot be isolated and should not be inferred from the quantitative results alone.

The positive relationship between motivation and perceived understanding provides a more specific contribution than merely showing that both dimensions received favorable ratings. Students who felt more willing to participate also tended to feel that they understood the scientific content better. One possible explanation, consistent with self-determination theory and evidence from virtual laboratory research, is that

motivated students invested more attention and cognitive effort in following the protocols and interpreting the simulated reactions (Ryan & Deci, 2020; Diwakar et al., 2023). The reverse interpretation is equally plausible: students who experienced greater clarity may have become more motivated to continue the activity. Because both variables were measured at the same time using self-reports, the direction of the relationship cannot be determined. It should therefore be interpreted as an exploratory association rather than as evidence that motivation caused perceived understanding or that perceived understanding caused motivation.

The high collaboration score is also noteworthy because students used individual computers. It suggests that individual access to the virtual environment did not necessarily lead to a socially isolated learning experience. The shared classroom setting, teacher guidance, and opportunities for peer exchange may have supported students' perception of collaboration. A recent review by Kurtz et al. (2025) showed that communication and group-awareness mechanisms can support knowledge sharing and collaborative learning in virtual and remote laboratories, while also noting that explicit tools for guiding and regulating collaboration remain insufficiently developed. In the present study, collaboration was assessed through students' perceptions rather than direct observation of their exchanges. The result therefore indicates a favorable social experience but does not demonstrate the quality or frequency of collaborative behavior.

The findings contribute to recent virtual-laboratory research in three specific ways. First, much of the recent school-level evidence has addressed physics, electricity, or chemistry, whereas this study focused on a Life and Earth Sciences activity involving the experimental identification of food constituents. Second, the study examined a resource-constrained instructional situation in which the comparison group received the same scientific content but had no access to physical or virtual manipulation. Third, the study examined objective post-test performance alongside five dimensions of students' experience. The contribution is consequently not the general claim that virtual laboratories improve learning, but the context-specific finding that a curriculum-aligned virtual environment can provide access to an experimental sequence when material laboratory access is unavailable, while supporting favorable perceptions of understanding, usability, motivation, and collaboration.

This contextual contribution also addresses a gap identified by Elmoazen et al. (2023), whose review found that virtual-laboratory research remains fragmented, frequently small-scale, and concentrated in higher education. The present investigation extends the evidence to lower-secondary Life and Earth Sciences in a Moroccan setting. At the same time, its findings should not be generalized beyond the conditions examined. Yang et al. (2024) reported an overall moderate positive effect of virtual reality on practical skills and found stronger effects when virtual practice was combined with conventional approaches. The considerably larger effect observed here may partly reflect the nature of the comparison condition, which did not include laboratory manipulation, as well as the limited sample. It should not be interpreted as evidence that LabInnov can replace physical practical work.

Several methodological constraints therefore delimit the conclusions. The post-test-only design did not establish baseline equivalence between the two classes, and the absence of individual randomization means that pre-existing differences may have contributed to the observed performance gap. The study involved only 34 students from one private school, the intervention lasted 240 minutes, and the questionnaire analyses were based on 17 respondents. In addition, the questionnaire was developed for this study, and its reliability coefficients provide only preliminary evidence. Future research should use larger, more diverse samples; pre-test and post-test measures; longer interventions; and comparisons across physical, virtual, and combined laboratory conditions. Direct observations or platform-generated interaction data would also help determine how students use virtual tools, collaborate, revise experimental decisions, and connect virtual procedures with subsequent physical manipulation.

## CONCLUSION

This pilot study showed that students who used LabInnov achieved higher conceptual and procedural knowledge scores than those receiving conventional non-laboratory instruction. Users also reported generally favorable perceptions of the platform, particularly regarding perceived understanding, usability, motivation, and collaboration. The study also found a positive association between motivation and perceived understanding. These findings suggest that LabInnov may complement practical science activities when material or organizational constraints limit

implementation. However, the results should be interpreted cautiously because of the small sample, the use of intact classes, and the absence of a pre-test. Further studies with larger samples and pre-test–post-test designs are needed to confirm these findings and examine whether they extend to other Life and Earth Sciences topics.

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