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THE DIDACTICS OF ERROR AND VISUAL REPRESENTATIONS IN THE DEVELOPMENT OF COMPETENCIES FOR AGRICULTURAL EXPERIMENTAL DESIGN: A COMPARATIVE STUDY OF FOUR COHORTS

Didáctica del error y representaciones visuales en el desarrollo de competencias para el diseño experimental agropecuario: estudio comparativo de cuatro cohortes

Segress García Hevia, Ph.D.[1]

Dr. Sheila Cárdenas García, M.S.[2]

Raúl Alejandro Montes de Oca Celeiro, B.A., M.A.[3]

Roberto Milanés Gómez, B.A., Ph.D.[4]

1 Universidad Bolivariana del Ecuador, Ecuador
2 Universidad ECOTEC, Ecuador
3 Universidad Bolivariana del Ecuador, Ecuador
4 Universidad de Guayaquil, Ecuador

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ABSTRACT

The objective was to evaluate the effect of an error-based teaching strategy mediated by visual representations on competencies for agricultural experimental design. A quantitative study was conducted using a pretest-posttest design with a comparison group (80 eighth-semester students divided into 4 consecutive academic cohorts). In , ten students in each cohort received the intervention, while the other ten received

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conventional instruction; this amounted to 16 class hours. The strategy included identifying methodological errors, analyzing consequences, reconstructing designs, scientific reasoning, and instructor feedback using diagrams, maps, and representations of experimental situations related to short-cycle crops. The reported results showed better final performance and fewer errors in the intervention group. The analysis of covariance, adjusted for initial performance and cohort, showed a favorable difference of approximately 1.33 points on a ten-point scale. It is thus concluded that the integrated strategy has the potential to strengthen methodological reasoning and experimental decision-making in technical and vocational agricultural education, although the specific effect of visual mediation could not be isolated.

Keywords: error didactics; visual representations; agricultural experimental design; technical and vocational education; research competencies; methodological reasoning.

RESUMEN

El objetivo fue evaluar el efecto de una estrategia de didáctica del error mediada por representaciones visuales en competencias para diseño experimental agropecuario. Se realizó una investigación cuantitativa con pretest postest y grupo de comparación (80 estudiantes octavo semestre repartidos en 4 cohortes académicas consecutivas). En cada cohorte diez estudiantes recibieron intervención y las otras diez enseñanzas convencionales; equivalía a 16 horas de clase. La estrategia incluía identificación de errores metodológicos, análisis de consecuencias, reconstrucción diseños, argumentación científica y retroalimentación docente mediante diagramas mapas y representación situaciones experimentales relacionadas cultivos ciclo corto. Los resultados reportados mostraron un mejor desempeño final y menor número de errores en el grupo intervención. El análisis covarianza ajustado por desempeño inicial y cohorte mostró diferencia favorable aproximada de 1,33 puntos en escala diez. Se concluye así que la estrategia integrada tiene potencial para fortalecer el razonamiento metodológico y toma de decisiones experimentales en formación técnica y profesional agropecuaria sin poder aislar el efecto específico de mediación visual.

Palabras clave: didáctica del error; representaciones visuales; diseño experimental agropecuario; formación técnica y profesional; competencias investigativas; razonamiento metodológico.

Abstract

The aim of this study was to test whether an error-based teaching strategy mediated by visual representations can develop competencies in agricultural experimental design. Quantitative experimental study with pretest, posttest, and comparison groups (80 eighth-semester students in four consecutive academic cohorts; ten students in the intervention group and ten in the conventional instruction group in each cohort, with equal duration of 16 hours). The strategy combined the identification

of methodological errors, analysis of consequences, reconstruction of experimental designs, scientific argumentation, and teacher feedback through diagrams, maps, and representations of experimental situations involving short-cycle crops. Final performance was higher in the intervention group, and methodological errors were reduced to a greater extent in the intervention group than in the control group. Analysis of covariance, adjusted for baseline performance and academic cohort, showed an approximate difference of 1.33 points on a ten-point scale in favor of the intervention. The integrated strategy may strengthen methodological reasoning and experimental decision-making in agricultural technical and vocational education; however, the independent contribution of visual mediation cannot be established based on the study design.

Keywords: error-based teaching, visual representations, agricultural experimental design, technical and vocational education, research competencies, methodological reasoning.

1. Introduction

Agricultural technical and vocational education faces the challenge of preparing individuals capable of understanding complex production problems. They must also propose solutions and justify their decisions using rigorous scientific methods. Changes in agricultural systems, demands for sustainability, variability in environmental conditions, and the integration of technologies into production processes require research skills. These skills help students move beyond merely repeating knowledge and enable them to generate, evaluate, and apply evidence according to the context. In this context, experimental design is a key component of scientific training. It provides the methodological and statistical principles needed to formulate hypotheses, make valid comparisons, control sources of variability, and support inferences about the phenomena under study.

In agricultural sciences, experimental design is used when conducting studies to evaluate plant varieties, fertilizers, irrigation systems, planting densities, phytosanitary practices, and production management technologies. The validity of these studies depends, among other factors, on the consistency between research objectives, the characteristics of the factors and treatments, the definition of experimental units, randomization, replication, and control of environmental heterogeneity. Thus, selecting a good experimental design is not merely a statistical decision but a process of scientific reasoning in which conceptual knowledge, methodological criteria, and specific experimental conditions converge.

This complexity places significant demands on university education. Declarative mastery of the principles of experimental design does not necessarily imply knowing the conditions under which they apply or being able to justify their use in the context of specific research problems. A student may know the general characteristics of a completely randomized design, a completely randomized block design, or a factorial arrangement, but may have difficulty deciding which one is appropriate for a given practical situation; or may correctly perform a statistical procedure but fail to realize

that the experimental structure used makes the observations independent or renders the valid inferences invalid. These situations highlight the need to strengthen methodological training aimed not only at learning about experimental designs but also at understanding them and scientifically justifying the decisions made.

Some difficulties that are particularly important in this process include confusion between the experimental unit and the observation unit, pseudo-replication, incorrect identification of factors and treatments, lack of randomization, insufficient blocking, and analytical procedures that are inappropriate for the structure of the experiment (errors that can reduce the precision of estimates; introduce bias; or lead to conclusions that do not correspond to the actual conditions of the research). From a pedagogical perspective, these errors should not be interpreted merely as incorrect answers but as conceptual, procedural, and inferential difficulties that can be examined to understand how students construct and apply their methodological knowledge.

In this sense, the pedagogy of error is an approach that turns mistakes into opportunities for analysis and reflection on knowledge, since it is based on the premise that learning depends not only on exposure to correct procedures but also on the ability to evaluate decisions, detect inconsistencies, and explain consequences and justified solutions. Safadi (2022) studies the diagnosis of erroneous examples in science learning; Alemdag et al. (2025) examine learning from incorrect examples and the pedagogical conditions that can facilitate it. Based on these contributions, we can conclude that the educational potential of errors lies not in the errors themselves but in the cognitive activities involved in their identification, explanation, and correction.

The pedagogical effectiveness of erroneous examples depends on the conditions under which students discover, explain, and rectify the inconsistencies present in a learning situation. In a systematic review, Dieterich et al. (2025) describe the conditions conducive to learning from incorrect examples and highlight the importance of active error processing. This approach provides the basis for the strategy used in this research: students were presented with experimental situations containing methodological inconsistencies and had to reconstruct them by making scientifically justified decisions. Thus, the error serves as a resource for promoting experimental reasoning because it requires students to establish relationships between statistical principles, characteristics of the research problem, and the consequences of the decisions made.

Learning from error is a process of cognitive reorganization in which the differences between the responses produced and the expected performance criteria serve as opportunities to review knowledge and reconstruct procedures. Zhang and Fiorella (2023) present an integrative model through which the role of errors in the construction of learning can be understood; however, the cognitive processes involved in their identification and processing must also be considered. Along the same lines, Narciss and Alemdag (2025) study the individual and contextual conditions that influence learning from errors and experiences of failure, arguing that the pedagogical use of errors must go beyond simply identifying them as incorrect results and include

activities involving explanation, reflection, and evidence-based reconstruction. In the teaching of agricultural experimental design, this is particularly relevant because methodological errors can invalidate research decisions and the interpretation of obtained results.

Applying this type of approach to the teaching of experimental design is particularly important because methodological errors have consequences beyond the classroom. Incorrect allocation of treatments, misuse of replicates, or the omission of relevant sources of variability can affect the understanding of results and the usefulness of technical recommendations derived from research. Thus, analyzing design errors through contextualized situations allows for linking statistical fundamentals to real-world problems in agricultural research. Similarly, Smucker et al. (2023) assert that it is necessary to integrate the teaching of experimental design with experiences that incorporate decisions regarding planning, execution, and analysis, which reinforces the fact that it is not enough to focus solely on the mechanical application of procedures.

However, detecting and reconstructing experimental errors is even more difficult when methodological relationships have a spatial, structural, or combinatorial dimension that is not always evident through verbal explanations. The distribution of plots, the order of treatments, the arrangement of blocks, the structure of factorial designs, and the relationships between experimental units and observations are configurations that can be expressed through various systems of representation (in this sense, scientific visual culture has epistemological and pedagogical value because it broadens our understanding of the processes through which students interpret, examine, and reconstruct experimental decisions).

From an epistemological perspective, visual representations are not merely illustrative resources for simplifying previously developed content. Scientific diagrams, graphs, sketches, and schematics organize, externalize, interpret, and communicate relationships that form part of the construction of knowledge (Tang, 2023). When discussing the characteristics of diagrams in scientific explanations, Tang points out that visual and written modes are integrated in the representation of meaning. In this way, we can understand how graphic and verbal information do not necessarily have equivalent functions, but rather can provide complementary semiotic resources for expressing scientific structures, relationships, and processes.

Visual representations are tools for organizing and interpreting scientific knowledge when they allow us to externalize spatial, structural, and functional relationships that are difficult to understand through verbal explanations alone. Lichtenberger et al. (2024), in their study of learning through multiple external representations in physics, demonstrate the importance of considering the conditions under which these resources are presented and used; from this perspective, the pedagogical value of a representation lies not only in its existence but also in the intellectual operations it promotes during learning. Plot sketches, randomization schemes, and treatment diagrams in agricultural experimental design allow us to visualize methodological

decisions, identify potential inconsistencies, and justify alternatives for experimental organization.

Scientific visual culture can thus be understood as a set of practices involving the production, interpretation, and communication of representations that play a role in the construction of knowledge. It is not enough simply to have images in teaching processes; rather, the necessary intellectual operations must be present to understand what information is being represented (and how), what the relationships are among its components (what decisions guide its construction), and what its explanatory possibilities and limitations are. From this perspective, a scientific representation should not be understood as a neutral and exhaustive reproduction of reality but rather as a selective construction that emphasizes certain aspects of the phenomenon and visually organizes the relationships considered relevant.

This understanding is related to the concept of metavisualization (the ability to reflect on visual representations, their characteristics, and their functions in the construction of scientific explanations). Chang (2022), in studying teacher and student metavisualization during scientific modeling, notes that epistemological knowledge, evaluation criteria, and metacognitive processes play a role in the use and assessment of representations. From this perspective, interpreting an experimental diagram involves not only recognizing the graphic elements but also determining whether the decisions it conveys are relevant and whether its structure is consistent with the methodological principles it aims to represent.

The relationship between spatial thinking and scientific learning provides another basis for explaining why these representations are important. Taylor et al. (2023) study the relationships between spatial thinking, visualizations, and learning in STEM disciplines, noting that the processes through which spatial relationships are organized, transformed, and interpreted are fundamental. In agricultural experimental design, this dimension is particularly relevant because methodological decisions are often physically reflected in production spaces: interpreting a plot layout involves recognizing where the experimental units are located, how treatments are related, conditions of heterogeneity, and possibilities for controlling sources of variation. Therefore, spatial representation can serve as a means of verifying whether the physical structure of the experiment aligns with statistical principles that ensure its validity.

Furthermore, the construction of scientific meaning requires the articulation of different modes of representation. Cheung et al. (2025) investigate how visual, verbal, and written modes interact in the way students construct meaning about the nature of science. This perspective helps us understand that the interpretation of a visual representation can be richer when accompanied by verbal explanations, written justifications, and processes of argumentation. In agricultural science, this integration occurs when a student interprets an experimental design, identifies an inconsistency, and explains why change X improves the alignment between the problem and design Y.

The use of multiple external representations should also be examined in terms of the conditions that enable their pedagogical application. Rexigel et al. (2024), through a systematic review and meta-analysis of the use of more than two external representations in STEM education, provide evidence to discuss the benefits and conditions for using different representational modalities. Thus, the inclusion of sketches, diagrams, decision tables, and factorial designs should not be considered beneficial simply because of the number of resources used, but rather because these representations align with the learning objectives and intellectual activities promoted during their interpretation.

From this perspective, visual representations have a dual role in the teaching of agricultural experimental design. First, they fulfill an epistemological function by externalizing the structure of methodological decisions, the relationships among their components, and the conditions necessary for a study to be valid; second, they fulfill a didactic function by providing objects of analysis for students to interpret, question, compare, and reconstruct. Both dimensions converge when the representation ceases to be used solely to demonstrate a correct procedure and instead becomes a means for critically examining the coherence of experimental decisions.

The intersection between scientific visual culture and the didactics of error is particularly important when representations incorporate methodological inconsistencies that must be identified and corrected: an experimental sketch in which treatments are misallocated, a diagram where subsamples are confused with independent replicates, or a representation that fails to control for an environmental gradient can all be problematic for scientific reasoning because they must be analyzed by recognizing the inconsistency, relating it to the fundamentals of experimental design, explaining its consequences, and reconstructing a methodologically valid alternative. Thus, the visual representation of the error ceases to be merely an illustration of an erroneous response and becomes a subject of scientific inquiry.

The reconstruction process is particularly relevant because it must lead from the initial identification of the error to a well-founded methodological decision. It is not enough to say that a treatment assignment does not work: one must explain why it compromises the control of variability, which experimental principles are affected, and justify a different design. Thus, visual mediation can be part of a pedagogical framework of identification, interpretation, explanation, reconstruction, and argumentation, where representations serve as concrete references for examining whether statistical knowledge corresponds to research decisions.

However, it is necessary to distinguish between the role of representations as part of an intervention-based pedagogy and the visual skills that can be assessed separately. McLure et al. (2022), in analyzing the diagrams created by students to explain scientific phenomena, demonstrate why explicit criteria are necessary to evaluate the quality of the representation and the meaning expressed therein; this is relevant to our study, since the representations were used as tools to analyze and reconstruct methodological errors, while learning was assessed based on specific competencies (selection,

structuring, and justification of experimental designs) and the frequency of methodological errors.

Thus, although the intervention activities required interpreting graphical and diagrammatic representations, the study did not aim to measure independent competencies in visual literacy, graphical decoding, or diagrammatic reasoning. Differences in performance across pedagogical conditions should therefore be understood in relation to the integrated error-based teaching strategy mediated by visual representations, without attributing to these representations an independent effect that the research design does not allow us to identify. This clarification establishes a necessary correspondence between conceptual foundation, variables actually assessed, and the scope of conclusions.

The articulation of these foundations allows us to identify a research issue. On the one hand, the literature on learning from error provides insights into why it is necessary to analyze incorrect responses and reconstruct knowledge; on the other hand, studies on scientific representations highlight their role in the organization, interpretation, and communication of meaning. However, the relationship between these two fields must be examined contextually when visual representations are used to study errors in agricultural experimental design and the competencies assessed are methodological decisions with direct implications for applied research.

The use of correct and incorrect examples in learning activities can aid in the analysis of misconceptions and the understanding of the procedures necessary to solve problems. Barbieri and Silla (2024) analyze the role that examples play in reducing misconceptions and fostering an understanding of procedures. This allows for the development of a strategy in which visual representations are not merely illustrative resources but critical objects to be analyzed. Thus, reconstructing a flawed experimental design involves recognizing its inconsistencies, explaining methodological consequences, and proposing an alternative configuration based on scientific principles. This approach forms the pedagogical foundation of the intervention under study.

In particular, the study examines whether participating in a strategy that combines error analysis, interpretation of visual representations, and reasoned reconstruction of experimental situations leads to differences in methodological performance compared to conventional teaching. This question is important because selecting an appropriate experimental design requires combining conceptual, statistical, and spatial information; recognizing contextual constraints; and justifying the coherence between the decisions made and the scientific objectives. Thus, the aim is not only to determine whether students achieve higher grades but also to analyze competencies related to design selection, identification of treatment factors, definition of experimental units, design-analysis correspondence, statistical analysis, reasoning, and methodological decisions.

Furthermore, studying different academic cohorts allowed us to analyze another important dimension of this issue: the temporal consistency of differences between pedagogical conditions. Results found in a single implementation may be related to participant characteristics, the academic period, or teaching conditions; therefore, examining four consecutive cohorts enables us to determine whether the differences between an integrated error-based teaching strategy and conventional teaching remain similar across different implementation periods. This approach expands the available comparative descriptive evidence in the context under study, but it does not in itself eliminate potential sources of confounding nor does it allow for the automatic generalization of the results to other populations.

In response to this challenge, the present study was conducted with 80 eighth-semester students in the agricultural technology program of a technical and vocational training institution, divided into four consecutive academic cohorts of 20 participants each. In each cohort, two pedagogical conditions were compared: an intervention focused on identifying, explaining, and reconstructing methodological errors through visual representations (one condition) and a conventional teaching condition. The evaluation included initial and final assessments of experimental design competencies as well as records of methodological errors to study differences between groups and student behavior across the four academic periods.

The scientific contribution of this study lies on two complementary levels. On a conceptual level, it integrates scientific visual culture, the didactics of error, and methodological reasoning to support a pedagogical strategy based on agricultural experimental design problems; on an empirical level, it compares performance and error frequency between two pedagogical conditions (pre- and post-tests across four consecutive cohorts). This allows for a discussion of the role of visual representations as interpretive objects and methodological reconstructions within an integrated process, while clearly defining their pedagogical function in relation to the effects that can be identified through the variables actually evaluated.

Based on this background, the following scientific question was then posed: To what extent does participation in an error-based teaching strategy mediated by visual representations result in differences in the development of competencies for agricultural experimental design and methodological errors compared to conventional teaching?

2. Methodology

The study employed a quantitative approach using a randomized parallel-group experimental design with pretest and posttest measurements and a control group. It was comparative and explanatory in nature, designed to evaluate differences in the development of agricultural experimental design competencies and the frequency of methodological errors between students who received an error-based teaching strategy mediated by visual representations and students who received conventional instruction.

The study included four consecutive academic cohorts of eighth-semester students in the technical and vocational agriculture program, conducted in 2025 and 2026. In each cohort, 20 students were randomly assigned to two instructional conditions: an intervention group consisting of 10 students and a control group with equal representation. Thus, there were 40 participants per condition and a total sample of 80 students.

The design included pre- and post-tests to observe changes occurring during the training process and to compare performance between the two pedagogical conditions. Random assignment within each cohort aimed to reduce initial differences between groups, while four academic terms allowed us to examine the consistency of the results across different implementations of the strategy.

The independent variable was the pedagogical condition (participation in the error-based teaching intervention mediated by visual representations or conventional teaching). The primary dependent variable was performance on agricultural experimental design competencies, scored on a scale of 0 to 10 points. As an additional outcome, the frequency of methodological errors was taken into account.

The interpretation of the results focused on the differences associated with the integrated pedagogical strategy. Since the intervention combined error analysis, visual representation, methodological reconstruction, and teacher feedback, the design did not allow for the separate identification of each component's contribution.

3.2. Context, Population, and Participants

The research was conducted within the Experimental Design course in the eighth semester of the technical and professional agricultural program, which aims to develop competencies in planning research, selecting experimental designs, identifying factors and treatments, defining experimental units, controlling sources of variability, and justifying statistical analysis procedures.

The accessible population consisted of students enrolled in the course during the four academic periods studied. The sample comprised 80 students distributed across 4 consecutive cohorts (20 participants per period).

In each cohort, 10 students were randomly assigned to the intervention group and 10 to the control group. Thus, the 40 participants were distributed across the two instructional conditions.

Eighth-semester students enrolled in Experimental Design were included. No additional exclusion criteria were established regarding academic performance or other individual characteristics.

The distribution by cohorts and pedagogical conditions is presented in Table 1.

Table 1.

Distribution of participants by academic cohort and instructional condition

Cohort	Intervention	Control	Total
Cohort 1	**10**	**10**	**20**
Cohort 2	**10**	**10**	**20**
Cohort 3	**10**	**10**	**20**
Cohort 4	**10**	**10**	**20**
Total	**40**	**40**	**80**

Source(s): García et al. Compiled by the author

Individual pretest and posttest scores were retained to compare students' initial and final measurements. Matched records were available for all 80 participants, ensuring that there were no follow-up losses.

The study was organized into four consecutive academic periods conducted between 2025 and 2026. Each period lasted approximately five months and corresponded to a separate cohort of eighth-semester students.

The pedagogical intervention took place over four consecutive weeks within each academic term (one weekly 4-hour session per cohort, for a total of 16 hours of intervention per month per cohort).

The intervention was carried out on different dates, according to the group's academic calendar. This allowed the strategies to be implemented successively, and the results of four independent implementations to be compared.

The study's timeline distinguished between the duration of the academic term (five months) and the specific duration of the pedagogical intervention (four weeks).

3.4 Methodological Rationale for the Pedagogical Intervention.

The intervention was based on the didactics of error as a learning strategy aimed at transforming methodological errors into opportunities for analysis, reflection, and the reconstruction of scientific knowledge.

Its pedagogical foundation was based on the fact that errors made when selecting and applying experimental designs are not merely incorrect answers but manifestations of conceptual, procedural, and inferential difficulties that can be systematically studied.

Three fundamental categories of errors were identified:

Conceptual errors. Also known as confusions: erroneous interpretations of the principles of experimental design (e.g., confusion between experimental unit and unit of observation; factors, levels, and treatments).

Execution errors. Related to the improper application of methodological procedures (treatment assignment, randomization, replication, and blocking).

Inference errors. Related to statistical interpretations or conclusions that do not correspond to the characteristics of the design used.

This classification made it possible to organize instructional activities according to the nature of the difficulties identified and to direct the feedback processes toward explaining their causes and consequences.

The strategy comprised four intellectual processes (identification of the error; explanation of its methodological implications; reconstruction of the experimental solution; and scientific justification of the decisions made). These were carried out in five instructional phases, including teacher feedback.

3.5. Visual Representations as Mediators of Experimental Learning.

The novelty of the intervention lay in the use of visual representations of experimental situations as tools for recognizing, analyzing, and correcting methodological errors.

The activities were conducted in research on short-cycle crops (problems related to experimental design selection, plot organization, distribution of treatments, definition of experimental units, factorial structures, and control of variability).

The graphical representations made it possible to externalize relationships among the components of an experiment and analyze the correspondence between the research problem, the design structure, and statistical possibilities.

Rather than finding just one correct answer, students had to interpret the information presented, identify inconsistencies among them, explain their consequences, and propose methodologically justified modifications.

An example of the above is the analysis of an experimental sketch with an incorrect distribution of treatments, which allowed for the study of randomization and variability control; similarly, the representation of plants grouped into plots enabled discussion of pseudo-replication and differences between experimental units and subsamples.

These situations served as tools for relating the abstract principles of experimental design to specific problems in agricultural research.

It is important to note that the visual representations were part of an integrated pedagogical intervention. Therefore, the study analyzed differences associated with the strategy as a whole and not the independent effect of the visual resources.

3.6 Organization and Implementation of the Intervention: Organization and Implementation of the Intervention.

The pedagogical sequence consisted of five interconnected stages:

First stage. Diagnosis and identification of the error. The first step was to diagnose and identify the problem. It is necessary to be clear about exactly what is happening in order to then seek possible solutions and attempt to resolve it. The students observed experimentally designed scenarios represented graphically to identify methodological inconsistencies and make an initial interpretation.

Second stage. Explanation of the consequences. Students were encouraged to analyze the potential effects of the detected errors on bias, the accuracy of estimates, the validity of results, and the possibilities for scientific inference.

Third stage. Methodological reconstruction. Students wrote alternative solutions by reorganizing treatments, experimental units, randomization procedures, replication, and control variables according to the characteristics of the problem.

Fourth stage. Scientific reasoning. The proposed solutions were justified using methodological and statistical principles (alignment between the research question, the chosen design, and the data analysis).

Fifth stage. Instructor feedback. Guidance and discussion sessions were held to explain inconsistencies, compare alternatives, and consolidate criteria for experimental decision-making.

The strategy was implemented through research scenarios involving short-cycle crops. The visual aids used included experimental design diagrams and other visual resources related to the methodological decisions analyzed.

The control group covered the content of the Experimental Design course using conventional methodology based on practical exercises involving short-cycle crops.

These activities were aimed at applying methodological and statistical principles to the selection of experimental designs, the identification of factors and treatments, the organization of experimental units, and situations typical of agricultural research.

Instruction took place over four consecutive weeks (4 hours per weekly session), for a total of 16 hours per cohort. The schedule was identical for the intervention group, allowing for a comparison of instructional exposure over time.

Both groups covered the course's basic content and engaged in activities related to research on short-cycle crops.

The main difference was the methodological strategy used: while the intervention group engaged in structured activities (identifying, explaining, and reconstructing errors using visual representations), the control group carried out conventional practices for applying experimental design knowledge.

The equivalence in duration between the pedagogical conditions reduced the influence of differences in teaching time as an alternative explanation for the results. However, this equivalence does not necessarily ensure that other confounding factors have been eliminated; therefore, the differences were interpreted while taking into account the participants' initial level and the characteristics of the four academic cohorts.

3. Results

The descriptive analysis of the four academic cohorts revealed differences between students who received the error-based teaching strategy mediated by visual representations and those who received conventional instruction in terms of the development of competencies in agricultural experimental design.

On the pretest, the means for both groups were relatively close. The control group scored between 8.30 and 8.43 points, while the intervention group scored between 8.23 and 8.57 points. This descriptive proximity indicates similar levels of initial performance but is not in itself statistical evidence of equivalence in pedagogical conditions.

After four weeks of implementation, the intervention group had mean scores of 9.87, 9.70, 9.85, and 10.00 points for the first, second, third, and fourth cohorts, respectively ( ). The control group obtained final scores of 8.51, 8.44, 8.66, and 8.42 points.

The final differences between the groups were 1.36, 1.26, 1.19, and 1.58 points, respectively, all in favor of the intervention. These results show a consistent pattern of higher final performance among students who participated in activities involving the identification, explanation, and reconstruction of experimental errors using visual representations.

In general terms, the approximate average increase was 1.47 points in the intervention group and 0.17 points in the control group. The descriptive difference between the two increases is approximately 1.30 points.

This shows that performance improvement was greater in the integrated pedagogical condition across the four academic periods. However, descriptive differences must be distinguished from the adjusted estimates obtained through covariance analysis.

The reduction in methodological errors in the intervention group can be explained by the formative role of identifying and correcting incorrect answers. Metcalfe et al. (2025) studied learning from errors versus explicit instruction and demonstrated the importance of certain feedback conditions; in this study, the reduction in errors occurred within a framework where the analysis of inconsistencies, methodological reconstruction, scientific argumentation, and mediation using visual representations were part of the integrated pedagogical approach; therefore, the results confirm the relevance of the integrated pedagogical approach but do not allow us to infer which specific component was most important for the observed reduction, nor whether the statistical differences should be interpreted as a comparison of final scores across

pedagogical conditions or as comparisons of initial means across pedagogical conditions.

The evaluation of methodological errors revealed differences between the pedagogical conditions in terms of both their final frequency and the magnitude of reduction observed during the learning process.

On the pretest, the intervention group had means ranging from 4.30 to 4.60 errors per student; the control group had means ranging from 4.10 to 4.30 errors. This indicates that the initial frequency of errors was slightly higher in the intervention group.

Reconstructing erroneous experimental situations led students to move from simply recognizing inconsistencies to providing well-founded explanations of their causes and consequences (Tulis & Dresel 2025), highlighting why it is important to encourage adaptive responses through activities involving reflection, correction, and feedback. In the study described, discussing methodological alternatives was the central focus of the intervention because it linked the understanding of experimental principles to scientific decision-making; however, without an independent evaluation of the pedagogical components, the observed differences cannot be attributed exclusively to feedback, reconstruction, or visual mediation.

At the end of the training process, the average error frequency for the intervention group was 0.80; 0.30; 0.20; and 0.10 for the first, second, third, and fourth cohorts, respectively. The absolute reductions were 3.70; 4.20; 4.40; and 4.20 errors per student.

In contrast, the control group had final error rates of 3.80; 3.80; 4.10; and 3.60 errors, with respective reductions of 0.30; 0.40; 0.20; and 0.60.

Overall, the mean error frequency in the intervention group decreased from approximately 4.48 to 0.35 errors per student (i.e., an absolute reduction of 4.13 errors), while in the control group it decreased from 4.20 to 3.83, with an approximate reduction of 0.38 errors.

The described factorial analysis of variance revealed statistically significant differences between the instructional conditions regarding posttest error frequency ($p < 0.0001$). The cohort effect ($p = 0.2276$) and the cohort-instructional condition interaction ($p = 0.2471$) did not reach statistical significance.

These results indicate that the lower final error rate in the intervention group occurred across all four academic periods. However, the inferential analysis conducted for this variable did not include an adjustment for the initial error rate; therefore, its results should be interpreted as a comparison of final values rather than an estimate adjusted for initial performance.

4.3. Analysis of Covariance of Final Performance

To verify whether differences in final performance persisted after accounting for initial scores and characteristics of the four academic cohorts, an analysis of covariance (ANCOVA) was used.

The posttest score was taken as the dependent variable, with the fixed factors being instructional condition and academic cohort; the pretest score served as the covariate.

The overall model was statistically significant with a p-value < 0.0001, a coefficient of determination $R^2 = 0.76$, and an adjusted R^2 of 0.75. This means that the variables included in the model together explained approximately 76% of the observed variability in the final scores.

From the perspective of technical and professional education, the results indicate that it is necessary to link methodological learning to real-world problems that require sound scientific decisions. Zhao and Selvaratnam (2024) systematically review transformations in professional education to examine how educational content is linked to practical demands. This makes sense for teaching agriculture and livestock science because the choice of experimental design, the organization of treatments, and the control of sources of variability are decisions that directly impact the quality of applied research (for example). In this sense, the strategy studied may serve as a pedagogical alternative for linking statistical fundamentals to real- y situations typical of agricultural and livestock production; however, the effective transfer of skills to research conducted outside the classroom requires further evaluation.

The adjusted difference between the pedagogical conditions was 1.33 points in favor of the treatment, with an estimated 95% confidence interval of 1.15 to 1.51 points for this difference. The initial score was also statistically associated with final performance, with p-values < 0.0001. The regression coefficient for the pretest was positive ($\beta = 0.35$), meaning that better initial performance was associated with higher final scores when the other terms in the model were included.

The main effect of the academic cohort, with a p-value of 0.2806, did not reach statistical significance across the four academic periods after adjusting for initial performance and instructional condition.

Overall, the ANCOVA showed that the differences in favor of the intervention persisted after accounting for initial scores and academic cohorts.

The combined analysis of the four cohorts revealed a descriptive pattern favoring the intervention. In all academic periods, students in the treatment group achieved higher final scores and made fewer methodological errors than participants in the control group.

The mean differences on the posttest ranged from 1.19 to 1.58 points, while the reductions in errors were greater for the intervention group across all four cohorts.

The factorial ANOVA of final performance did not find a statistically significant interaction between cohort and instructional condition, with a p-value of 0.5904. Furthermore, and coincidentally, the analysis of final errors also did not show a significant interaction, with a p-value of 0.2471.

These results show that there was insufficient statistical evidence that the differences between instructional conditions varied by cohort; however, the lack of statistical significance for the interactions does not imply that the effects were the same across academic periods. Each cohort consisted of 20 students (two groups of 10 participants); therefore, the sample size limits the precision with which potential differences in the intervention's effectiveness across academic periods can be estimated.

The use of ANCOVA involves examining the relationship between the initial covariate and final performance (specifically, whether the regression slopes are homogeneous across instructional conditions).

The interaction test between pretest scores and pedagogical condition using sequential analysis of sums of squares revealed p-values > 0.9999.

This test found no statistical evidence of differences in regression slopes across pedagogical conditions, which is consistent with using an ANCOVA model with common slopes.

However, the fact that the interaction is not significant does not, in and of itself, prove that all model assumptions are met. This verification must be conducted by examining the residuals, outliers, and the model's fit to an outcome variable ranging from 0 to 10 points.

The strength of the association between instructional condition and final performance was highest within the adjusted model, with a value of 0.736. However, this measure does not correspond to the percentage of learning induced by the intervention. Rather, it represents the proportion of partial variation attributable to the condition

One of the notable aspects was the performance of the fourth cohort, in which the intervention group achieved a posttest mean of 10.00 points. This concentration of scores at the upper end of the scale is consistent with a ceiling effect: when students reach the maximum score, the instrument cannot distinguish differences among high levels of performance.

Therefore, the significance of the results must be evaluated by integrating descriptive differences, adjusted estimates, effect sizes, and instrument limitations.

The descriptive and inferential results showed differences in favor of the intervention group in final performance regarding agricultural experimental design and the reduction of methodological errors.

Improved performance was observed across all four academic cohorts and persisted after adjusting for initial scores and academic term. The adjusted difference was 1.33

points on a scale of 0 to 10; the instructional condition was statistically associated with the final outcome.

Furthermore, the mean frequency of methodological errors decreased more in the intervention group than in the control group, providing additional evidence of differences between pedagogical conditions.

These results demonstrate the need for further research into strategies that integrate error analysis, the interpretation of visual representations, and the reasoned reconstruction of experimental decisions. Their interpretation must be linked to the characteristics of the integrated intervention, the properties of the instrument, and the assumptions of the applied statistical analysis.

4. Conclusions

The error-based teaching strategy mediated by visual representations improved competencies in agricultural experimental design compared to conventional teaching, with a p-value < 0.0001 across the four cohorts studied, although it remained statistically significant after adjusting for initial performance and academic term ($p < 0.0001$), with an advantage of 1.33 points (95% CI: 1.15–1.51).

The intervention was also associated with fewer methodological errors, particularly in processes related to experimental design selection, treatment structuring, and the rationale for research decisions. These results highlight the need to incorporate critical error analysis, solution reconstruction, and visual representations into agricultural science education.

The main novelty of the study is that it provides evidence that this integrated pedagogical strategy can improve methodological reasoning; however, the independent effect of visual mediation cannot be inferred because the study design does not allow for this. Future research will need to analyze its specific components, the retention of learning, and the transfer of these skills to real-world agricultural research situations.

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AUTHORS

Ing. Segress García Hevia, PhD [1] https://orcid.org/0000-0002-6178-9872 Bolivarian University of Ecuador, Ecuador

Dr. Sheila Cárdenas García, M.Sc. [2] https://orcid.org/0009-0001-8433-2912 ECOTEC University, Ecuador

Raúl Alejandro Montes de Oca Celeiro, B.A., M.A. [3] https://orcid.org/0000-0001-8733-9610 **Bolivarian University of Ecuador, Ecuador**

Roberto Milanés Gómez, Lcdo., PhD[4]https://orcid.org/0000-0002-6879-3559,roberto.milanesg@ug.edu.ec University of Guayaquil, Ecuador