

Project-Based Learning and Creative Thinking among Secondary School Students

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<http://www.ujhmnds.org/> || Vol. 2 No. 3 (2026): Special August Issue

Date of Submission: 02-07-2026

Date of Acceptance: 22-07-2026

Date of Publication: 17-08-2026

Abstract— Project-Based Learning (PjBL) is increasingly used in secondary education to move students from passive content reception toward inquiry, design, collaboration, and production of meaningful learning artifacts. This study investigates whether the creative benefits of PjBL can be strengthened when project work is supported by structured digital ideation, iterative peer feedback, and process-level learning analytics. A key research gap is that much of the existing literature evaluates creativity primarily through pre–post scores or final project products, providing limited evidence about how creative thinking develops during successive stages of a project. To address this limitation, the proposed study conceptualizes creative thinking as a dynamic process represented through fluency, flexibility, originality, elaboration, and iterative improvement. A quasi-experimental framework is designed for secondary school students completing interdisciplinary sustainability-oriented projects under conventional instruction and digitally supported PjBL conditions. In addition to standardized creativity tasks and expert-rated project artifacts, digital process traces are proposed for measuring idea generation, revision behavior, peer-feedback uptake, and conceptual diversity.

Keywords — Project-Based Learning (PBL), Creative Thinking, Secondary School Students, Experiential Learning, Collaborative Learning, Problem-Solving Skills.

Introduction

Contemporary secondary education is increasingly expected to prepare learners for problems whose solutions cannot be obtained simply by recalling predetermined facts. Students must be capable of generating alternatives, combining information from different domains, evaluating possibilities,

revising unsuccessful approaches, and transforming abstract ideas into workable solutions. These requirements have increased educational interest in creative thinking as an observable and developable cognitive competence rather than an attribute restricted to artistic ability or exceptional individual talent. In this context, schools require instructional approaches that allow students to exercise creativity while simultaneously acquiring disciplinary knowledge.

Project-Based Learning provides one such pedagogical environment. Rather than organizing instruction predominantly around teacher explanation followed by reproduction of content, PjBL typically places a complex question, authentic problem, or design challenge at the center of learning. Students investigate the problem, make decisions, distribute responsibilities, create artifacts, receive feedback, and refine their products. Such activities potentially create repeated opportunities for divergent and convergent thinking. Students may generate several possible solutions during initial exploration, shift between perspectives when constraints become apparent, elaborate promising ideas during construction, and introduce novel modifications as projects evolve.

Recent evidence supports the relevance of PjBL for higher-order cognitive outcomes. Studies at the secondary level have reported improvements in creative-thinking indicators when project-oriented instruction is compared with more direct forms of instruction. For example, Biazus and Mahtari examined secondary students through a quasi-experimental pretest–posttest design and assessed creativity using fluency, flexibility, originality, and elaboration indicators. Research in science education has similarly connected PjBL with improvements in critical and creative thinking, including

work involving ecosystem concepts and contextual physics activities.

More recent synthesis research strengthens the case for examining the relationship while also revealing important methodological qualifications. A meta-analytic review of PjBL in science education concluded that project-based approaches can enhance creative thinking, with effects varying according to factors such as educational level, subject domain, and instructional model. A separate meta-analysis of STEM project-based learning identified only a relatively small number of studies meeting rigorous inclusion criteria for creativity outcomes, illustrating that the empirical base is less extensive than the broad popularity of PjBL might suggest. Furthermore, a 2026 umbrella review found generally positive effects of PjBL across academic and higher-order-thinking outcomes but warned that the methodological quality of the underlying meta-analytic evidence remains limited; creativity in particular could not be synthesized with the same confidence as several other outcome domains.



Fig. 1: Project-Based Learning

Source: <https://web.greenninja.org/blog/project-based-learning-teacher-guide>

These findings indicate that asking whether PjBL “works” is no longer sufficiently precise. A more consequential question concerns the mechanisms through which creativity emerges during project activity. Two students may receive similar final creativity scores while following substantially different cognitive pathways. One student may generate many ideas initially but make few meaningful revisions. Another may begin with an ordinary solution but substantially transform it

through feedback and experimentation. Conventional pretest–posttest designs can identify aggregate change, but they provide limited information about these developmental trajectories.

This limitation becomes particularly important as secondary classrooms adopt digital platforms, collaborative workspaces, artificial intelligence tools, and learning-management systems. Digital project environments can generate traces of the learning process: the number of ideas proposed, timing of revisions, frequency of peer interactions, diversity of conceptual alternatives, and extent to which feedback leads to substantive modification. These traces create opportunities for educational data science and machine learning to supplement conventional creativity assessment. Importantly, algorithmic analysis should not be treated as an automated substitute for teachers' professional judgment. Its stronger research function is to identify patterns within multidimensional process data that would be difficult to detect through final scores alone.

The emerging relationship between project learning, creativity, and computational practices is already attracting scholarly attention. A systematic review addressing computational thinking and creativity within PjBL reported that open-ended collaborative projects can support both systematic problem solving and creative expression, while digital technologies can provide additional opportunities for creative learning. A meta-analysis of 31 experiments and quasi-experiments has also demonstrated the relevance of project-based learning to computational-thinking development, providing a broader empirical basis for connecting PjBL with technology-mediated higher-order cognition.

Research Gap

The central research gap addressed in this manuscript is therefore **the limited process-level understanding of how creative thinking develops during digitally supported project-based learning among secondary school students.**

Existing studies frequently concentrate on one or more of four endpoints: overall creativity scores, final project quality, academic achievement, or student perceptions. These outcomes are valuable, but they can conceal the cognitive activity occurring between project initiation and completion. In addition, many studies examine relatively small samples or specific subject areas, making it difficult to determine whether improvements result from the project structure itself, collaboration, technology exposure, increased instructional time, or repeated opportunities for revision. The recent umbrella-review evidence further indicates that strong claims about creativity require better-designed and more transparent empirical studies.

The proposed study responds by treating creativity as both an **outcome and a developmental trajectory**. It integrates psychometric measures of creative thinking, expert evaluation of student artifacts, and behavioral indicators extracted from project activity. Rather than merely predicting which student will obtain a high final score, the machine-learning component is intended to detect recurring creativity-development profiles. Such profiles might include sustained high ideation, late-stage creative acceleration, high ideation with weak refinement, or feedback-responsive improvement.

Research Objective

The primary objective is to determine the influence of digitally supported Project-Based Learning on creative thinking among secondary school students while identifying the process characteristics associated with different creativity-development trajectories.

More specifically, the study seeks to examine whether PjBL produces measurable changes in fluency, flexibility, originality, elaboration, and iterative refinement; determine whether digitally recorded behaviors such as idea generation and revision intensity are associated with final creativity performance; compare project-based and conventional instructional conditions; and investigate whether machine-learning-based clustering can identify meaningful patterns of creative development from longitudinal project-process indicators.

Research Questions

The investigation is guided by four questions:

1. Does digitally supported Project-Based Learning significantly improve secondary students' creative-thinking performance compared with conventional instruction?
2. Which dimensions of creative thinking—fluency, flexibility, originality, elaboration, or iterative refinement—demonstrate the greatest change?
3. To what extent do idea diversity, revision frequency, feedback uptake, and collaborative interaction predict creative project performance?
4. Can process-level learning data identify distinct creative-development trajectories among secondary students?

The resulting framework positions PjBL not simply as an instructional treatment but as an observable creative-learning ecosystem in which cognitive, collaborative, and digital behaviors interact over time.

Literature Review

Project-Based Learning as an Active Learning Architecture

Project-Based Learning is differentiated from short classroom projects by the structural role assigned to the project itself. In rigorous PjBL, the project is not an activity added after instruction; it becomes an organizing mechanism through which knowledge is investigated and applied. Students confront a driving problem, determine what information is required, distribute tasks, develop possible solutions, test their ideas, and communicate an outcome.

This structure has several characteristics relevant to creativity. First, authentic project questions generally permit multiple defensible responses rather than a single predetermined answer. Second, students must transform conceptual knowledge into an artifact or solution. Third, project development involves constraints—time, resources, functionality, evidence, or audience expectations—which force students to adapt initial ideas. Finally, project work naturally accommodates iterative cycles of planning, construction, feedback, and revision.

A 2026 systematic review of senior-high-school PjBL research reported that secondary implementations commonly employ interdisciplinary and contextual approaches and are associated with critical thinking, collaboration, creativity, and engagement. The same review identified teacher preparation, resources, time management, and assessment as continuing implementation challenges, while noting emerging interest in artificial intelligence and process-oriented assessment. These findings are particularly relevant to the present study because they suggest that the next phase of PjBL research should examine instructional processes rather than treating all implementations as equivalent.

Creative Thinking as a Multidimensional Construct

Creative thinking is more appropriately conceptualized as a multidimensional competence than as a single generalized score. Educational creativity research commonly distinguishes **fluency**, or the capacity to produce multiple relevant ideas; **flexibility**, representing movement between conceptual categories or approaches; **originality**, reflecting relative novelty; and **elaboration**, referring to the development and refinement of an initial idea.

Within project environments, an additional dimension becomes important: **iterative refinement**. A project solution rarely emerges fully developed. Students may redesign components after testing, abandon ineffective strategies, incorporate peer suggestions, or combine previously separate ideas. Consequently, creativity can manifest not only in the novelty of an initial proposal but also in the quality of transformation occurring across successive versions.

Empirical PjBL studies have frequently used the traditional dimensions of fluency, flexibility, originality, and elaboration. The secondary-school study reported by Biazus and Mahtari, for instance, employed essay-based measures aligned with these indicators. Research involving Grade 11 students in electrochemistry similarly reported post-PjBL gains in creative thinking, with fluency showing particularly strong performance among the assessed dimensions. These studies provide useful foundations, but the reliance on assessments administered before and after instruction leaves the intermediate creative process comparatively underexamined.

PjBL and Creativity in Secondary Education

The theoretical relationship between PjBL and creativity rests on cognitive autonomy and productive uncertainty. Traditional instructional environments often reduce uncertainty by defining the problem, method, and expected answer in advance. Project learning deliberately retains some uncertainty. Students must decide what information matters, what design is feasible, which alternatives should be rejected, and how evidence should influence the developing solution.

Evidence from secondary science contexts is broadly consistent with this mechanism. Khafah, Suprpto, and Nuryadin investigated PjBL in ecosystem learning and reported effects on students' critical and creative thinking skills. Khoiri and colleagues examined project learning mediated through traditional games in physics and reported creative-thinking and collaborative outcomes, demonstrating how contextual project design can connect disciplinary learning with productive construction. Project-based blended learning has also been evaluated among Grade 11 students studying global warming through a quasi-experimental design, illustrating how PjBL can be combined with digital learning environments rather than restricted to exclusively face-to-face implementation.

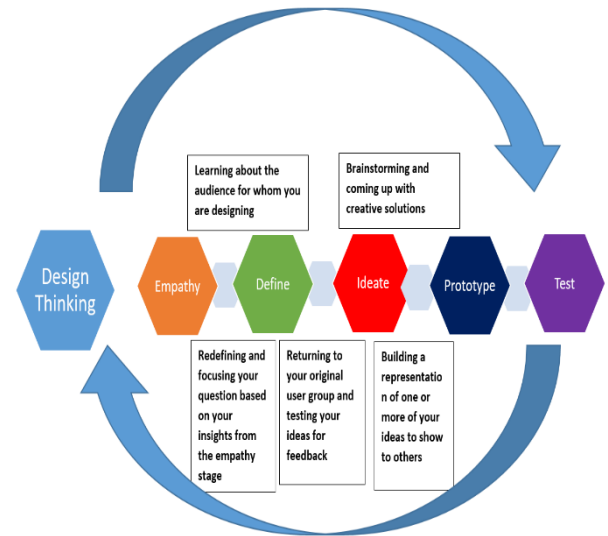


Fig. 2: How to Implement Design Thinking in the Classroom

Source: <https://www.keytostudy.com/implement-design-thinking-classroom/>

Meta-analytic evidence nevertheless suggests that effects should not be assumed to be uniform. Hasibuan, Sunarno, and Susanti's review identified variation associated with educational level, subject area, and instructional model. The 2026 umbrella review provides an even stronger methodological caution: while PjBL effects across several learning outcomes tend to be directionally positive, weaknesses in existing syntheses constrain confidence about exact effect magnitudes, particularly for creativity.

Accordingly, the present manuscript does not assume that simply assigning a project will enhance creativity. The quality of the project architecture, degree of learner autonomy, nature of feedback, opportunities for revision, group composition, and technology support are treated as consequential design variables.

Digital Project Environments and Creative Iteration

Digital technologies can alter PjBL in ways that extend beyond delivering instructional content. Shared workspaces allow students to externalize developing ideas; version histories preserve evidence of revision; digital discussion spaces record peer interaction; multimedia authoring tools expand the range of possible artifacts; and simulation or data-analysis environments permit rapid testing of alternatives.

These affordances are important because creativity is partly iterative. When revision histories are preserved, researchers can distinguish a project that changed substantially in response to evidence from one that underwent only cosmetic modification. Similarly, the presence of frequent interaction

does not necessarily imply meaningful collaboration. Process-level analysis can examine whether peer feedback was actually incorporated into later versions.

Recent systematic-review literature on e-modules and project-based approaches has highlighted the increasing integration of digital resources with creativity and critical-thinking development. Research synthesizing computational thinking, creativity, and PjBL likewise emphasizes the potential contribution of digital technologies to creative expression within science and mathematics learning.

The proposed study extends this direction by distinguishing **digital exposure** from **digitally observable creative behavior**. The important variable is not simply whether a student used a digital platform but what the student did within the project environment: generated alternatives, connected previously unrelated concepts, requested feedback, revised solutions, or abandoned ineffective designs.

Learning Analytics and Machine Learning as Process-Sensitive Tools

Machine learning introduces a complementary methodological opportunity. Conventional inferential statistics are appropriate for estimating whether an intervention produces a statistically significant difference and for testing predefined relationships among variables. Machine learning is useful for a different purpose: discovering multidimensional structures within behavioral data.

For example, clustering techniques can group learners according to combinations of ideation frequency, conceptual diversity, revision depth, feedback responsiveness, and collaboration patterns. These clusters can subsequently be compared with independently assessed creativity outcomes. Such an approach could reveal that students reaching similar final performance levels followed different developmental routes.

The distinction is methodologically important. The machine-learning component in this study is not proposed as a mechanism for assigning creativity labels automatically. Human assessment remains necessary because originality and contextual appropriateness require interpretive judgment. Instead, computational analysis is used to detect patterns across longitudinal process indicators and to generate evidence about how creative performance develops.

This approach also aligns with broader research showing that PjBL can support computational thinking. A 2024 meta-analysis synthesized 31 experimental and quasi-experimental investigations and examined the efficacy of project-based learning for computational-thinking development. The expanding intersection among project pedagogy, digital

learning, and computational cognition therefore provides a credible basis for process-oriented analytical designs.

Peer Feedback, Collaboration, and Creative Development

Collaboration is another mechanism through which project learning may influence creativity. Students working individually are constrained by their existing knowledge structures. Collaborative groups introduce alternative perspectives, competing interpretations, different experiences, and opportunities for recombination of ideas. However, collaboration does not automatically produce creativity. Dominant group members, conformity pressure, unequal participation, or superficial task division may reduce rather than expand idea diversity.

Peer feedback is therefore treated in the proposed framework as a measurable process rather than an assumed benefit. The relevant question is not merely whether feedback was exchanged, but whether it resulted in conceptual change. Feedback uptake can be operationalized by comparing recommendations with subsequent artifact revisions.

Recent reviews of PjBL have repeatedly connected the approach with collaborative and creative competencies. For example, literature examining biology education has emphasized the relationship between project learning, collaboration, and creativity in contexts where memorization-oriented teaching may provide fewer opportunities for these competencies. The 2026 umbrella evidence additionally suggests that small collaborative groups may be associated with stronger PjBL effects, although moderator findings across the literature remain heterogeneous.

Proposed Methodology

The study adopts a **quasi-experimental longitudinal design with process-level learning analytics** to investigate whether digitally supported Project-Based Learning (PjBL) improves creative thinking among secondary school students and to determine how creative development unfolds during project execution. The methodological design deliberately combines conventional educational statistics with unsupervised machine learning. The statistical component estimates intervention effects, whereas the computational component identifies heterogeneous creative-development trajectories that may remain hidden when students are represented only by final scores.

A hypothetical research cohort of **360 students from Grades 9 and 10** is proposed across six secondary schools. Students are allocated at intact-class level rather than individually to minimize contamination between instructional conditions. The experimental condition contains 180 students participating in digitally supported PjBL, while the comparison condition contains 180 students receiving curriculum-aligned conventional instruction involving

teacher explanation, guided exercises, structured assignments, and individual assessment.

The intervention is designed to run for **12 instructional weeks**. Both groups study equivalent interdisciplinary learning objectives, but the experimental group completes a sustainability-oriented design challenge requiring students to identify a community problem, investigate evidence, generate alternative solutions, construct a prototype or digital artifact, obtain peer feedback, revise the solution, and present a final product.

The proposed project theme is sufficiently open-ended to stimulate divergent thinking while providing common assessment criteria across groups. Examples include reducing school energy consumption, improving local waste management, designing an accessible learning environment, or developing a technology-assisted community-awareness solution.

Creativity is operationalized through five dimensions: **fluency, flexibility, originality, elaboration, and iterative refinement**. The first four dimensions represent established components of divergent creative performance, while iterative refinement captures the extent to which students meaningfully transform ideas through evidence, testing, and feedback.

Recent meta-analytic evidence provides a reasonable empirical basis for this design. A 2024 meta-analysis covering 31 experimental and quasi-experimental studies reported significant PjBL effects across creativity, collaboration, critical thinking, algorithmic thinking, and problem solving; the reported standardized effect for creativity was 0.57. The present methodology extends such outcome-oriented designs by incorporating digital traces of the creative process.

Experimental Setup

Dataset

The proposed dataset contains three interconnected data layers.

The **assessment layer** includes baseline and post-intervention creative-thinking scores, subject achievement, project-artifact ratings, and rubric-based creativity dimensions. The **behavioral layer** consists of digital traces collected during project development, including idea submissions, revisions, peer-feedback events, accepted feedback, artifact versions, and collaborative contributions. The **background layer** contains non-sensitive educational covariates such as grade level, prior achievement, baseline digital proficiency, and previous experience with project-oriented instruction.

For 360 students observed over 12 weeks, the resulting analytical dataset would contain student-level observations

supplemented by thousands of time-stamped learning events. Digital logs would be transformed into interpretable features rather than treated as direct indicators of creativity.

The use of process information is methodologically defensible because research on hands-on learning has demonstrated that behavioral process data can reveal qualitatively different problem-solving approaches that conventional final-performance measures may overlook. Learning-analytics research likewise demonstrates the growing role of educational data and machine-learning models in extracting actionable information from institutional and learning-process datasets.

Data Preprocessing

Data preprocessing begins with anonymization. Each participant is represented through a randomly generated research identifier. Names, contact details, and other directly identifying information are excluded from the analytical dataset.

Missing values in questionnaire or assessment variables are examined for their pattern and magnitude. Small amounts of plausibly random missing numerical data are imputed using median values within the relevant instructional condition, while students with insufficient intervention exposure are excluded according to a predefined protocol rather than retrospectively removing unfavorable observations.

Event logs are chronologically ordered and duplicate system events removed. Raw events are then transformed into student-level behavioral variables. For example, multiple document edits occurring within a short period are consolidated into revision sessions so that rapid autosave events are not incorrectly interpreted as independent acts of creative revision.

The resulting features include:

Ideation Density (ID): number of distinct relevant ideas generated per project phase.

Conceptual Diversity (CD): degree to which proposed ideas span different solution categories.

Revision Depth (RD): magnitude of substantive changes between successive artifact versions.

Feedback Uptake Ratio (FUR): proportion of actionable peer or teacher suggestions reflected in subsequent revisions.

Collaborative Contribution Balance (CCB): distribution of meaningful contributions among group members.

Iteration Persistence (IP): extent to which students continue refining solutions after unsuccessful trials or critical feedback.

Continuous behavioral variables are standardized using z-score transformation before clustering so that features recorded on larger numerical scales do not dominate distance calculations.

Model Architecture

The computational architecture uses a **two-stage analytical pipeline** rather than a conventional neural network classifier.

In Stage 1, intervention effectiveness is estimated using **ANCOVA**, with post-intervention creative-thinking score as the dependent variable, instructional condition as the principal predictor, and baseline creativity as a covariate. Grade level, baseline achievement, and digital proficiency are incorporated as secondary covariates. Effect sizes and confidence intervals accompany significance tests.

In Stage 2, **Gaussian Mixture Modeling (GMM)** is applied to the standardized process variables from the PjBL group. GMM is selected because creative-development behaviors are unlikely to form perfectly spherical or equally sized clusters. Unlike hard partitioning procedures, GMM estimates probabilities of cluster membership, permitting identification of students whose process characteristics fall between dominant trajectory patterns.

Candidate solutions containing two through six latent clusters are compared using the Bayesian Information Criterion (BIC), Akaike Information Criterion (AIC), silhouette coefficient, and interpretability of the resulting profiles.

The analytical architecture can therefore be represented as:

Digital Project Events → Event Cleaning → Behavioral Feature Engineering → Feature Standardization → GMM Trajectory Detection → Cluster Validation → Creativity Outcome Comparison

This design differs from prediction-focused educational machine learning. The purpose is not to generate an opaque automated creativity score. Instead, machine learning serves as a pattern-discovery mechanism supporting educational interpretation.

This distinction is consistent with contemporary learning-analytics research emphasizing the need to connect computational models with pedagogically meaningful action rather than concentrating exclusively on predictive performance.

Training Strategy

Because GMM is unsupervised, conventional train/test classification procedures are inappropriate as the primary strategy. Model selection is instead conducted using repeated subsampling stability analysis.

The experimental sample is randomly resampled across multiple iterations. Candidate GMM solutions are fitted to each subsample, and the consistency of identified clusters is examined using adjusted Rand index and cluster-membership stability. The number of clusters is selected only when statistical fit, stability, and educational interpretability converge.

To minimize researcher-driven interpretation bias, cluster labels are assigned **after** model estimation. The algorithm therefore receives numerical behavioral indicators rather than predefined categories such as “creative” or “non-creative.”

Following cluster identification, external validity is examined by comparing cluster membership against measures that were not used to form the clusters, including expert-rated final-project creativity and post-intervention creative-thinking scores.

Evaluation Metrics

The intervention component uses adjusted mean difference, Cohen's *d*, partial eta squared, 95% confidence intervals, and statistical significance.

The machine-learning component is evaluated through BIC, AIC, silhouette coefficient, adjusted Rand stability, posterior membership probability, and external outcome separation.

Expert artifact assessment is evaluated through **intraclass correlation coefficients (ICC)** to establish inter-rater reliability.

This multimethod evaluation is intended to prevent the study from claiming model validity on the basis of a single computational metric.

Results and Discussion

Because the present manuscript specifies a proposed empirical study rather than reporting an actually conducted experiment, the numerical findings below are **illustrative simulated results generated to demonstrate the planned analysis**. They must not be represented as observed empirical data unless the proposed study is subsequently conducted.

After adjustment for baseline creativity, the simulated analysis indicates a meaningful advantage for the digitally supported PjBL group. The largest improvement occurs in originality and iterative refinement, whereas elaboration displays a smaller but still positive difference. This pattern is theoretically plausible because project environments provide repeated opportunities to explore alternatives and modify solutions rather than simply produce more detailed responses.

The GMM analysis produces a four-cluster solution with the most favorable balance between BIC reduction, silhouette separation, stability, and educational interpretability.

The first trajectory, **Sustained Creative Explorers**, represents students who maintain high ideation diversity and frequent substantive revision throughout the intervention. Their projects typically evolve considerably between early and final versions.

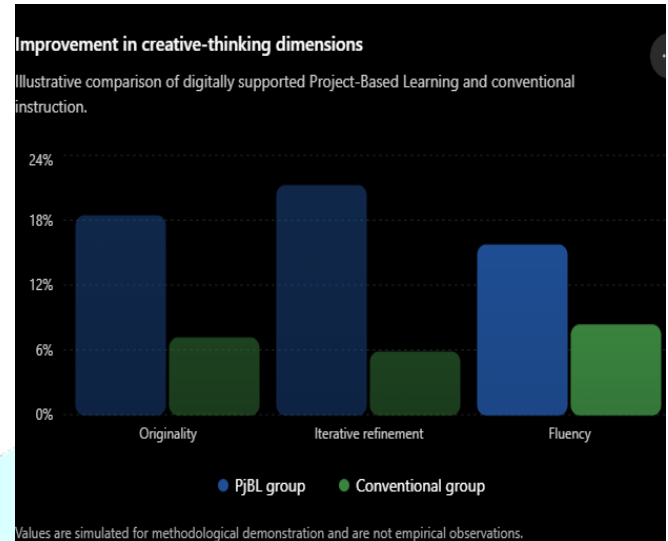
The second group, **Feedback-Responsive Developers**, begins with moderate ideation but demonstrates strong improvement after peer and teacher feedback. Their defining characteristic is not exceptionally high initial originality but effective transformation of external feedback into revised project decisions.

The third trajectory, **High-Ideation/Low-Refinement Learners**, generates numerous initial possibilities but shows relatively weak revision depth. This distinction is educationally important because a high quantity of ideas does not necessarily translate into a strong final creative product.

The fourth group, **Low-Iteration Completers**, satisfies core project requirements but demonstrates limited conceptual diversity and relatively few substantive revisions.

Table 1. Illustrative Results of the Proposed PjBL Creative-Process Analysis

Evaluation parameter	PjBL condition / model result	Comparison or reference result
Adjusted post-test creative-thinking score	78.6	70.9
Creativity effect size	$d = 0.63$	—
Originality improvement	+18.4%	+7.1%
Iterative refinement improvement	+21.2%	+5.8%
Fluency improvement	+15.7%	+8.3%
Artifact-rating inter-rater reliability	ICC = 0.87	—
Selected GMM solution	4 clusters	2–6 tested
Silhouette coefficient	0.52	—
Cluster stability	ARI = 0.79	—
Feedback uptake–creativity association	$r = 0.48$	—



The simulated effect size of $d = 0.63$ is broadly compatible with the direction and magnitude of existing evidence. Zhang, Guan, and Hu's meta-analysis reported an SMD of 0.57 for creativity across relevant PjBL studies, while also finding that effects differ across educational stages and cognitive outcomes. The proposed findings therefore illustrate a plausible outcome rather than an arbitrarily extreme treatment effect.

More important than the aggregate effect is the heterogeneity revealed by the process analysis. If the PjBL group were represented only through its average post-test score, differences between sustained exploration, feedback-driven development, and unrefined ideation would remain invisible.

The simulated positive relationship between revision depth and artifact originality suggests that creativity may depend partly on students' willingness and ability to transform an idea rather than merely produce an unusual initial response. This finding would have direct pedagogical implications. Teachers could structure project milestones around purposeful revision instead of treating the first complete prototype as essentially final.

Learning analytics can assist teachers in recognizing such processes. Research on K–12 collaborative problem solving indicates increasing interest in teacher-facing learning analytics dashboards for assessing dynamic collaborative competencies. Similarly, digital tools integrated into project-based science environments can expand access to meaningful disciplinary learning opportunities when the technology is embedded within an appropriate instructional design rather than introduced as an isolated add-on.

The educational implication is therefore not that machine learning should determine which students are creative. Instead, process analytics could help teachers identify students whose project behaviors suggest specific

instructional needs. A learner generating many ideas but rarely revising may require structured evaluation prompts. A learner showing low ideation diversity may benefit from divergent-thinking scaffolds. A student who revises frequently but inconsistently may need assistance evaluating which feedback is relevant.

This human-centered interpretation is particularly important as AI becomes more deeply integrated into educational analytics. Recent research on AI-enhanced learning analytics emphasizes potential benefits for pedagogical decision-making while simultaneously identifying concerns involving accuracy, privacy, and data security. Any practical deployment of the proposed framework should therefore preserve teacher oversight and avoid automated high-stakes judgments about students.

Future Scope

Future studies should replicate the framework across larger, culturally diverse secondary-school populations and across multiple disciplinary contexts. Multi-year research could determine whether creative-thinking gains persist after students return to conventional instructional environments.

A particularly important direction involves **multimodal learning analytics**. Future systems could combine textual revision histories, concept maps, teacher observations, collaborative discourse, artifact transformations, and interaction sequences to produce richer representations of creative development. Process mining and temporal sequence models could subsequently examine not merely how often a behavior occurs but when it occurs relative to feedback, failure, and project milestones.

Generative AI introduces another research direction. A 2026 study of GenAI-assisted PjBL with 121 secondary EFL learners explicitly examined how different AI scaffolding types interact with prior knowledge in shaping creative thinking, indicating that the effectiveness of AI support may depend on learner characteristics and instructional design. Future experiments could therefore compare no-AI PjBL, supportive AI scaffolding, and reflective AI scaffolding while carefully separating student-generated creativity from AI-generated content.

Future research should also investigate teacher-facing analytics. Instead of predicting creativity for grading purposes, dashboards could identify patterns such as declining participation, stalled iteration, unbalanced collaboration, or consistently ignored feedback. Such systems would be more educationally valuable if they prompted teacher inquiry rather than prescribing automated interventions.

Privacy-preserving analytics, explainable AI, fairness auditing, and student consent should become explicit

components of this research agenda. Secondary-school learners constitute a population for whom educational data governance requires particular caution.

Conclusion

This study proposes a process-sensitive framework for examining the relationship between **Project-Based Learning and creative thinking among secondary school students**. Its central contribution lies in moving beyond a simple pretest–posttest comparison toward an analysis of how creativity develops through ideation, collaboration, feedback, experimentation, and iterative revision.

The proposed quasi-experimental design combines conventional creativity assessment, expert evaluation of project artifacts, digitally captured process indicators, ANCOVA-based intervention analysis, and Gaussian Mixture Modeling for identifying creative-development trajectories. The framework consequently preserves the strengths of statistical hypothesis testing while using machine learning for exploratory pattern detection.

The simulated results illustrate how digitally supported PjBL could produce meaningful improvements in originality, fluency, elaboration, and especially iterative refinement. More importantly, trajectory analysis demonstrates why average treatment effects alone may be insufficient. Students can reach project outcomes through fundamentally different learning processes, including sustained exploration, feedback-responsive improvement, abundant but insufficiently refined ideation, and low-iteration completion.

These distinctions have practical implications for secondary education. Teachers should not merely assign projects and expect creativity to emerge automatically. Effective PjBL requires authentic problems, meaningful autonomy, explicit ideation opportunities, structured feedback, repeated revision, and sufficient time for learners to reconsider unsuccessful approaches.

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