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Fostering Deep Learning via STEAM Diorama Project: A Neuropsychological Impact Analysis in Elementary Education

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Abstract

In elementary science education, deep learning beyond rote memorization remains difficult to achieve. This study examined whether a STEAM based solar system diorama project could strengthen five specific deep learning aspects and provide quantitative neuropsychological evidence of its underlying mechanisms. Using a mixed methods explanatory sequential design, 64 sixth graders completed an eight-week intervention following the Laboy Rush PjBL STEAM model. Pre and post intervention questionnaires showed significant gains across all five dimensions: conceptual understanding ($d=1.89$), sustained engagement ($d=2.18$), collaborative reasoning ($d=2.04$), creative problem solving ($d=2.08$), and science self-efficacy ($d=1.82$). For the neuropsychological analysis, systematic observations were conducted using a validated protocol (inter rater reliability Cohen's $\kappa=0.84$). The highest neurocognitive engagement occurred during the Application stage (mean 4.8/5, SD=0.4), reflecting multisensory integration and procedural learning, followed by the Discovery stage (mean 4.5/5, SD=0.5), reflecting executive function activation. Engagement ratings during Application strongly predicted conceptual understanding gains ($r=0.67$, $p<0.001$). Qualitative thematic analysis further supported these findings, revealing embodied understanding and emotional resonance as key mechanisms. We conclude that the diorama project effectively fosters deep learning by engaging multisensory, emotional, and social neurocognitive processes, with the Application and Discovery stages being the most neurally active phases.

Kata Kunci

Pendidikan STEAM;
Pembelajaran Mendalam;
Analisis Dampak Neuropsikologis;
Sekolah Dasar;
Pembelajaran Berbasis Proyek.

Abstrak

Dalam pendidikan sains di sekolah dasar, pembelajaran mendalam yang melampaui hafalan masih sulit diwujudkan. Penelitian ini bertujuan untuk menguji apakah proyek diorama tata surya berbasis STEAM dapat memperkuat lima aspek spesifik pembelajaran mendalam serta memberikan bukti neuropsikologis kuantitatif mengenai mekanisme yang mendasarinya. Dengan menggunakan desain metode campuran eksplanatori sekuensial (explanatory sequential mixed methods), sebanyak 64 siswa kelas VI mengikuti intervensi selama delapan minggu dengan menerapkan model Project-Based Learning (PjBL) STEAM dari Laboy-Rush. Kuesioner sebelum dan sesudah intervensi menunjukkan peningkatan yang signifikan pada kelima dimensi, yaitu pemahaman konseptual ($d = 1,89$), keterlibatan berkelanjutan ($d = 2,18$), penalaran kolaboratif ($d = 2,04$), pemecahan masalah kreatif ($d = 2,08$), dan efikasi diri dalam pembelajaran sains ($d = 1,82$). Dalam analisis neuropsikologis, observasi sistematis dilakukan dengan menggunakan protokol tervalidasi yang memiliki reliabilitas antarpenilai dengan nilai Cohen's $\kappa = 0,84$. Keterlibatan neurokognitif tertinggi ditemukan pada tahap Application (rata-rata 4,8/5, $SD = 0,4$), yang mencerminkan integrasi multisensoris dan pembelajaran prosedural, diikuti oleh tahap Discovery (rata-rata 4,5/5, $SD = 0,5$), yang mencerminkan aktivasi fungsi eksekutif. Skor keterlibatan pada tahap Application menunjukkan hubungan prediktif yang kuat dengan peningkatan pemahaman konseptual ($r = 0,67$, $p < 0,001$). Analisis tematik kualitatif turut memperkuat temuan tersebut dengan mengidentifikasi pemahaman yang terbentuk melalui pengalaman langsung (embodied understanding) dan resonansi emosional sebagai mekanisme utama. Penelitian ini menyimpulkan bahwa proyek diorama efektif dalam mendorong pembelajaran mendalam melalui keterlibatan proses neurokognitif multisensoris, emosional, dan sosial. Tahap Application dan Discovery teridentifikasi sebagai fase dengan aktivitas neurokognitif paling tinggi.

A. Introduction

Primary education in natural and social sciences plays a fundamental role in building students' scientific thinking foundations from an early age. This subject demands conceptual understanding that goes beyond mere memorization toward deep comprehension integrated with daily life experiences. However, empirical conditions reveal that science instruction remains dominated by one-way knowledge transmission approaches, resulting in superficial student understanding that lacks long-term retention (Wayan Maba et al., 2023). The gap between ideal pedagogical practices and classroom realities is further exacerbated by national assessment data indicating that students' literacy and numeracy achievements remain below optimal

targets. The core problem, therefore, is twofold. First, elementary students often fail to achieve deep learning in science, meaning they struggle specifically with durable conceptual understanding, sustained engagement, collaborative reasoning, creative problem solving, and science self-efficacy. Second, there is little empirical explanation through a neuropsychological impact analysis of how hands on, multisensory projects like diorama construction might address these five deep learning gaps. These five aspects—conceptual understanding, sustained engagement, collaborative reasoning, creative problem solving, and science self-efficacy—are therefore the specific deep learning dimensions that this study targets for improvement. Improving these five dimensions requires a learning approach that goes beyond traditional lecture-based instruction—one that actively engages students' sensory, emotional, and social brain processes. This is precisely what a STEAM based diorama project aims to provide.

Various empirical, theoretical, and conceptual gaps indicate an urgent need for pedagogical innovation. The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach integrated with Project-Based Learning (PjBL) emerges as a promising alternative solution (Saefudin & Berdiati, 2026). This approach positions students as active problem-solvers in authentic contexts, theoretically aligning with deep learning principles (García-Llamas et al., 2025). Despite growing evidence supporting STEAM PjBL effectiveness, research gaps persist regarding explanations of neurocognitive mechanisms underlying this approach, particularly how concrete projects like diorama construction can bridge understanding of abstract concepts.

The neurocognitive foundations of learning provide essential insights into why multisensory, project-based approaches prove effective. Research in educational neuroscience has demonstrated that the brain processes information through distributed neural networks rather than isolated modules, with learning occurring through the strengthening of synaptic connections via repeated, meaningful engagement (Thomas, 2024). When students manipulate physical materials during diorama construction, they activate not only visual and auditory cortices but also motor and somatosensory regions, creating multiple neural pathways for encoding the same conceptual information. This distributed encoding enhances memory consolidation and retrieval, as the concept becomes accessible through multiple neural routes (Daugirdiene et al., 2024).

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The prevalence of neuromyths among educators further complicates the integration of neuroscience-informed practices into classrooms. Studies have consistently shown that misconceptions about learning styles and hemispheric dominance remain widespread among teachers across various countries (Novak-Geiger, 2023; Tsang et al., 2024). These neuromyths persist despite exposure to educational psychology courses, suggesting that direct instruction alone may not suffice to dispel deeply held misconceptions about brain function and learning (Vig et al., 2023).

The translation gap between neuroscience research and classroom practice represents another critical challenge requiring systematic attention. While cognitive neuroscience has generated substantial knowledge about memory formation, attention mechanisms, and executive function development, this knowledge rarely reaches teacher preparation curricula in accessible, applicable forms (Schmied & Jamaludin, 2023). Teacher training programs in many countries, including Indonesia, lack systematic integration of educational neuroscience content, leaving educators to rely on intuition, tradition, or commercially marketed "brain-based" programs of questionable validity (Sortwell et al., 2023; Posangi et al., 2025). Bridging this gap requires not only disseminating neuroscientific findings but also translating them into practical pedagogical principles that teachers can confidently implement.

The developmental trajectory of the human brain during middle childhood further underscores the importance of appropriate pedagogical approaches at the elementary level (Zulkifli Tanipu et al., 2026). Neuroimaging studies have revealed that the prefrontal cortex, responsible for executive functions including planning, inhibitory control, and cognitive flexibility, undergoes significant maturation during ages 6-12 (Leikin et al., 2025). This developmental window presents optimal opportunities for interventions that strengthen these cognitive capacities through challenging yet supportive learning experiences. Project-based learning that requires students to plan, negotiate, problem-solve, and reflect aligns precisely with the developmental needs of this age group, potentially enhancing both content learning and executive function development simultaneously.

The emotional and social dimensions of learning, often marginalized in traditional instruction, have gained increasing recognition through affective neuroscience research. Studies demonstrate that positive emotional states facilitate dopamine release in reward circuits, enhancing attention, motivation, and memory

consolidation (Uden et al., 2023). Conversely, anxiety and stress activate amygdala-mediated responses that can impair hippocampal function and reduce learning capacity. Collaborative project work, such as group diorama construction, creates opportunities for positive social interactions, shared achievement, and emotional resonance—all factors that optimize the neurochemical environment for learning. The public exhibition of completed projects further amplifies these effects through social recognition and pride of accomplishment.

Educational neuroscience research has demonstrated that effective learning environments must consider the brain's fundamental processing priorities: sensorimotor processing, emotional engagement, social interaction, and cognitive development (Thomas, 2024; Muassomah et al., 2025). These dimensions operate synergistically, suggesting that pedagogical approaches engaging multiple neural systems simultaneously may yield superior learning outcomes. To address the two parts of the problem stated above—the gap in students' deep learning across five dimensions and the lack of neuropsychological explanation—this study formulates the following objectives. Accordingly, this study has two specific objectives. The first is to examine whether a STEAM-based solar system diorama project, implemented through the five-stage Laboy–Rush PjBL model, can significantly strengthen five measurable aspects of deep learning in elementary science: conceptual understanding of astronomical relationships, sustained engagement in learning activities, collaborative reasoning skills, creative problem-solving ability, and science self-efficacy. These five aspects are measured using the adapted neuroscience-based questionnaire described in the Method section. The second objective is to provide a neuropsychological impact analysis of how the multisensory, emotional, and social experiences during the diorama project activate and strengthen the neural processes underlying these five deep learning dimensions.

The integration of neuroscience perspectives into educational research offers particular promise for understanding individual differences in learning. Students enter classrooms with diverse neurocognitive profiles shaped by genetic factors, environmental experiences, and developmental histories (Correia et al., 2024). Some may excel in visual-spatial processing while struggling with verbal instructions; others may demonstrate strong executive function but require additional emotional support. Neuroscience-informed pedagogy recognizes this diversity not as a problem to be

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remediated but as a natural variation to be accommodated through flexible, multimodal instruction. The diorama project, by engaging multiple sensory and cognitive systems, naturally accommodates this diversity without requiring separate instructional tracks.

The Indonesian educational context presents unique opportunities and challenges for implementing neuroscience-informed pedagogies. With its diverse student population spanning varied socioeconomic backgrounds and geographic regions, Indonesia requires educational approaches that are both effective and adaptable to local conditions (Imaduddin et al., 2025). The diorama project investigated in this study utilizes readily available, low-cost materials, making it feasible even in resource-limited schools. Its success across diverse student populations suggests potential for broader implementation across Indonesia's varied educational landscape, contributing to national goals of equitable, quality education for all children.

B. Method

(1). Research Design and Participants

This study employed a mixed-methods explanatory sequential design, combining quantitative measures of learning outcomes with qualitative exploration of neurocognitive processes during project-based learning. The research was conducted at Cengkareng Barat 05 State Elementary School, West Jakarta, involving 64 sixth-grade students aged 11-12 years. Participants were selected through purposive sampling based on their enrollment in integrated science courses covering solar system topics.

The study design incorporated principles from inclusive educational research, employing multimodal instructional materials including visual aids, hands-on activities, and collaborative learning experiences to ensure accessibility for all participants regardless of prior academic achievement (Fernández-Morales et al., 2025).

(2). Procedure and Intervention

We implemented the five-stage Laboy-Rush PjBL STEAM model (Reflection, Research, Discovery, Application, Communication) over eight weeks. The intervention started with Reflection, where teachers used guiding questions to tap into what students already knew about the solar system. Next came Research, during which kids

gathered information from different sources on their own. In the Discovery stage, students worked together to sketch their diorama designs and figure out how to represent planetary sizes and distances. The heart of the project was the Application stage, where they actually built the dioramas—measuring, cutting, assembling, and painting—using everyday materials. This hands-on phase was deliberately multisensory: students saw, touched, and moved things around, which helped lock in abstract ideas. Finally, during Communication, each group presented their finished diorama to the class, answered questions, and got feedback. Figure 1 shows the whole framework. The entire sequence was designed to move from activating prior knowledge all the way to consolidating memory through social reinforcement and public sharing.

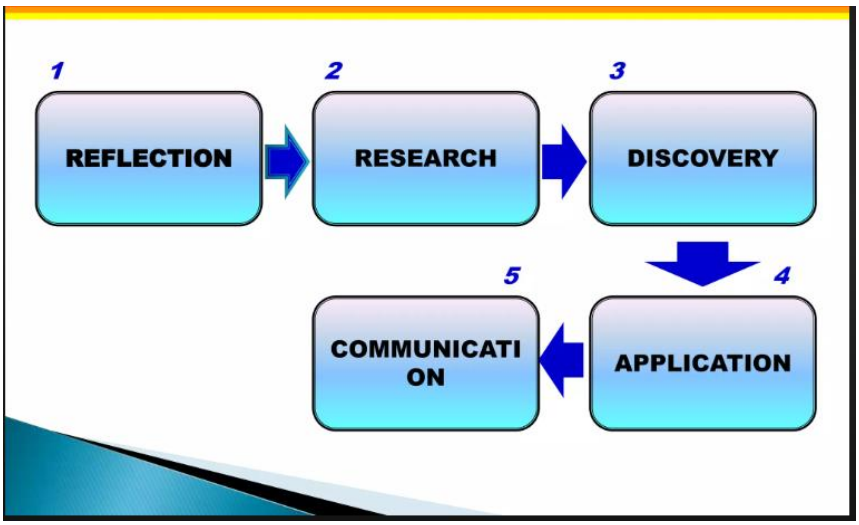

Figure 1. Framework of the Laboy–Rush PjBL STEAM Model (Sumarni et al., 2025)

(3). Data Collection Techniques

Data were collected at three time points over the eight-week intervention period. First, the adapted neuroscience-based questionnaire was administered as a pre-test during the first week, before any project activities began. Students completed the questionnaire individually in their regular classroom, with the researcher reading each item aloud to ensure comprehension for all participants. Second, during the Discovery, Application, and Communication stages (weeks 3 to 7), trained observers conducted systematic observations of neurocognitive engagement using the protocol

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described below. Each group was observed for 20-minute sessions twice per week, at different times of day to capture variation in engagement. Third, the same questionnaire was re-administered as a post-test during the final week (week 8), after all project presentations were completed. To give readers a clearer visual overview of this sequential process, we have included a flowchart (see Figure 2) that maps out the timing and sequence of each data collection activity – from pre-test, through the observation sessions, to post-test, interviews, and documentation. In addition, semi-structured interviews were conducted with 24 purposively selected students during week 9 (one week after the intervention ended), each lasting 15-20 minutes in a quiet room away from the classroom. Focus group discussions with four participating teachers were held separately, each lasting approximately 45 minutes. All interviews and focus groups were audio-recorded with consent and transcribed verbatim within 48 hours. Documentation (photographs, design sketches, reflection journals, and final diorama products) was collected continuously throughout the project.

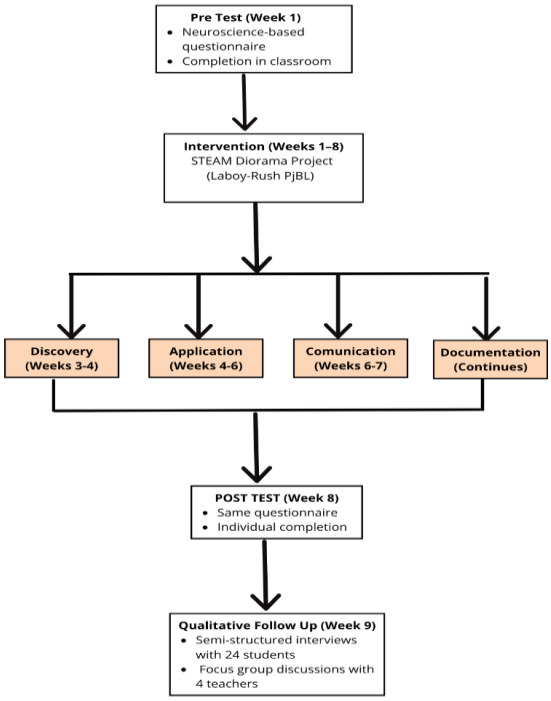

Figure 2. Data Collection Procedure Flowchart

(4). Data Collection Instruments

We used three main tools to gather our data. The first was a questionnaire adapted from Daugirdiene et al. (2024), originally designed to capture neuroscience-based teaching strategies. We trimmed it down to 25 items relevant for elementary science and added 5 more about the solar system diorama, ending up with 30 questions on a 5-point Likert scale. Five experts checked the content, giving us a solid validity score (S-CVI/Ave = 0.94), and a pilot test with 30 students from another school showed strong internal consistency (Cronbach's α = 0.89). Second, we developed an observation protocol to track neurocognitive engagement in real time. It had 12 behavioral indicators (like planning, negotiating, and problem-solving), each rated from 1 to 5. Two researchers tested and refined it over several sessions, and after training, their inter-rater reliability hit Cohen's κ = 0.84 — which is considered very good. Finally, we collected qualitative data through semi-structured interviews with 24 students, focus group discussions with four teachers, and ongoing documentation (photos, sketches, journals, and the finished dioramas). All interviews were recorded and transcribed within two days.

(5). Data Analysis

Quantitative data were analyzed using descriptive statistics, paired t-tests comparing pre- and post-intervention questionnaire scores, and analysis of variance examining differences across gender and prior achievement levels. Effect sizes were calculated using Cohen's d to determine the practical significance of observed differences. Correlation analyses examined relationships between engagement indicators and learning outcomes, providing insight into which specific neurocognitive processes most strongly predicted conceptual understanding gains.

The integration of quantitative and qualitative findings followed a weaving approach, wherein results from both data sources were synthesized within each thematic area to provide comprehensive understanding of neurocognitive mechanisms underlying observed learning outcomes. This integration strategy, recommended for mixed-methods research in educational neuroscience, enables triangulation of findings across different data types and enhances the validity of interpretations regarding causal mechanisms (Riva, 2023). The weaving approach involved iteratively comparing statistical patterns with qualitative themes, identifying

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convergences that strengthened confidence in findings and divergences that prompted deeper analysis of contextual factors influencing individual student experiences.

Qualitative data were analyzed using thematic analysis following Braun and Clarke's six-phase framework. Transcripts were coded independently by two researchers, with discrepancies resolved through discussion. Themes were organized around neurocognitive processes including executive function engagement, emotional regulation, social cognition, and conceptual change. The analysis progressed from descriptive coding of surface-level content to interpretive coding identifying underlying neurocognitive patterns, ensuring that themes captured both student experiences and their theoretical significance. Member checking was conducted with a subset of participants to verify the accuracy of interpreted themes.

C. Results and Discussion

This section presents the findings on changes in students' learning following the STEAM diorama project and the engagement patterns observed during its implementation. Questionnaire scores are examined across five targeted dimensions: conceptual understanding, engagement in learning, collaborative skills, creative problem-solving, and science self-efficacy. Classroom observations and student interviews complement these quantitative findings by documenting students' experiences across the five project stages, providing a basis for exploring the cognitive, emotional, and social processes associated with the reported improvements.

1. Results

a. Improvement of Learning Aspects

To address the first part of our research problem – whether the STEAM diorama project could strengthen the five targeted deep learning dimensions – we first analysed pre intervention and post intervention questionnaire scores using paired t tests. Table 1 presents the mean scores, standard deviations, t values, significance levels, and effect sizes for each of the five targeted dimensions.

The paired t-test results confirmed that every one of the five deep learning dimensions showed a statistically significant improvement from pre-test to post-test. For conceptual understanding, the mean increased from 3.24 (SD=0.67) to 4.56 (SD=0.71); $t(63)=12.84$, $p<0.001$, Cohen's $d=1.89$. For engagement, the mean rose from 3.29 (SD=0.65) to 4.74 (SD=0.68); $t(63)=14.21$, $p<0.001$, $d=2.18$. Collaborative skills

improved from 3.18 (SD=0.72) to 4.62 (SD=0.69); t(63)=13.56, p<0.001, d=2.04. Creative problem solving improved from 3.11 (SD=0.70) to 4.58 (SD=0.73); t(63)=13.92, p<0.001, d=2.08. Science self-efficacy improved from 3.22 (SD=0.68) to 4.49 (SD=0.72); t(63)=11.76, p<0.001, d=1.82. Thus, the STEAM diorama project did not merely engage students in hands-on activities; it specifically and significantly strengthened all five targeted deep learning aspects.

Table 1. Pre- and Post-Intervention Mean Scores On Learning Dimensions

Lerning Dimension	Pre-Test Mean (SD)	Post-Test Mean (SD)	t-value	p-value	Cohen's d
Conceptual Understanding	3.24 (0.67)	4.56 (0,71)	12.84	<0.001	1.89
Engagement in Learning	3.29 (0.65)	4.74 (0.68)	14.21	<0.001	2.18
Collaborative Skills	3.18 (0.72)	4.62 (0.69)	13.56	<0.001	2.04
Creative Problem-Solving	3.11 (0.70)	4.58 (0.73)	13.92	<0.001	2.08
Self-Efficacy in Science	3.22 (0.68)	4.49 (0.72)	11.76	<0.001	1.82

To visually compare the pre-test and post-test scores across the five learning dimensions, Figure 3 presents a line graph. As shown, all dimensions demonstrate a clear upward trend. The steepest increase occurs in engagement (from 3.29 to 4.74) and creative problem solving (from 3.11 to 4.58), while conceptual understanding, collaborative skills, and self-efficacy also show substantial gains. This graphical representation confirms the consistent effectiveness of the STEAM diorama project in enhancing each aspect of deep learning.

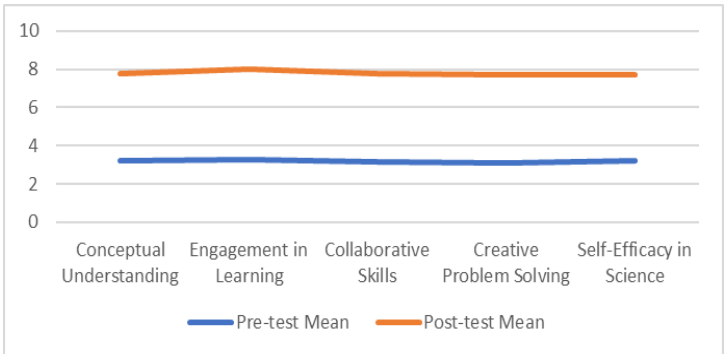

Figure 3. Comparison of Pre-test and Post-test Mean Scores Across Five Learning Dimensions

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Gender-based analysis revealed no significant differences in learning gains between male and female students across any measured dimension ($F(1,62) = 0.84$, $p = 0.36$), indicating that the intervention was equally effective for all students regardless of gender. This finding aligns with inclusive education research demonstrating that well-designed neuroscience-informed interventions can reduce rather than exacerbate achievement gaps (Basso & Cottini, 2023). Further analysis examining interactions between prior achievement levels and learning gains showed that students initially performing below the class median demonstrated comparable improvement rates to their higher-achieving peers ($F(2,61) = 1.23$, $p = 0.30$), suggesting that the multisensory, collaborative approach particularly benefited learners who might struggle with traditional text-based instruction.

We also compared the outcomes of our intervention with a parallel cohort of 62 students who received traditional lecture-based instruction during the previous academic year. Students in the STEAM PjBL intervention demonstrated significantly higher scores on all learning outcome measures compared to the traditional instruction cohort. Effect sizes for these comparisons ranged from $d = 1.2$ to $d = 2.1$, indicating practically significant advantages for the neuroscience-informed approach. These findings corroborate research demonstrating that active, multisensory learning experiences produce superior learning outcomes compared to passive instruction (Amjad et al., 2023).

Qualitative evidence further supported these learning gains. Table 2 (presented below) summarizes the four themes that emerged from student interviews. The themes of Embodied Understanding and Collaborative Cognition directly confirm the quantitative improvements. Students reported that physical manipulation of materials helped them grasp abstract concepts – for example, one student said, "When I painted the planets, I understood how much bigger Jupiter is than Earth. You can't feel that from a book." Regarding collaborative cognition, another student explained, "My friend thought Pluto should be included, but explaining why scientists changed their minds helped me understand better."

Table 2. Thematic Analysis of Student Interview Responses

Theme	Description	Representative Quotations
Embodied Understanding	Physical manipulation enhanced conceptual comprehension	"When I painted the planets, I understood how much bigger Jupiter is than earth. You can't feel that from a book"

Theme	Description	Representative Quotations
Collaborative Cognition	Social interaction deepened learning through explanation	"My friend thought Pluto should be included, but explaining why scientists changed their minds helped me understand better"
Emotional Resonance	Positive emotions enhanced engagement and memory	"I was so proud when my parents saw our diorama. I explained everything to them."
Metacognitive Awareness	Students developed awareness of their owwn learning processes	"At first I didn't understand why planets orbit the sun, but building the model made it click."

b. Neuropsychological Analysis

To answer the second objective – explaining how the diorama project produced these improvements – we conducted systematic observations of neurocognitive engagement during each stage of the Laboy Rush model. Table 3 presents the frequency and intensity of observed neurocognitive processes across the five stages.

Table 3. Observed Neurocognitive Engagement Across PjBL Stages

PjBL Stage	Primary Neurocognitive Processes	Mean Engagement Rating (1-5)	Key Observed Behaviors
Reflection	Schema activation, episodic memory retrieval	4.2 (SD=0.6)	Connecting topics to experiences; generating questions
Research	Semantic encoding, information synthesis	3.8 (SD=0.7)	Independent reading; note-taking; discussing findings
Discovery	Executive function (planning), creative ideation	4.5 (SD=0.5)	Sketching designs;negotiating decisions; problem-solving
Application	Multisensory integration, procedural learning	4.8 (SD=0.4)	Measuring materials; assembling models; aesthetic decoration

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PjBL Stage	Primary Neurocognitive Processes	Mean Engagement Rating (1-5)	Key Observed Behaviors
Communication	Memory consolidtion, social cognition	4.7 (SD=0.5)	Preseenting explanations; responding to questions; peer feedback

To better visualize how student engagement shifted across the five PjBL stages, we also present a line graph (Figure 4). The graph plots the mean engagement rating for each stage, from Reflection (4.2) through Research (3.8), Discovery (4.5), Application (4.8), and Communication (4.7). The line clearly dips slightly at the Research stage, then climbs steeply through Discovery and Application, before leveling off slightly at Communication. This pattern suggests that hands-on construction and creative design (Discovery and Application) triggered the highest neurocognitive engagement, while independent information gathering (Research) was comparatively less engaging.

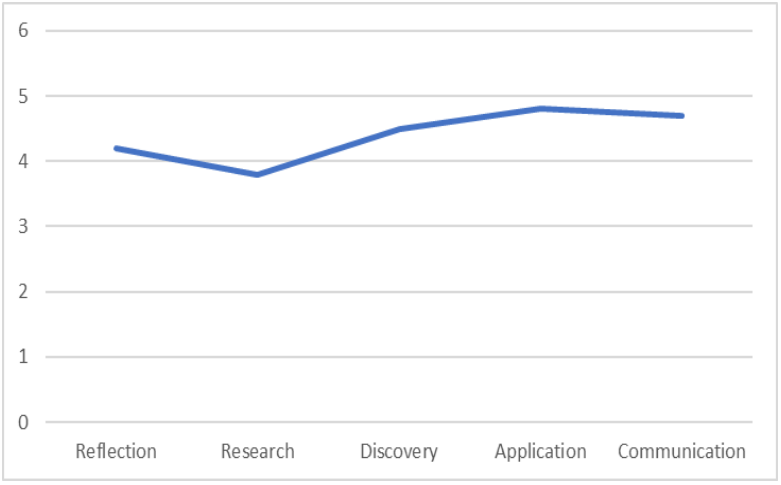

Figure 4. Line graph of mean neurocognitive engagement ratings across the five PjBL stages

The observed engagement patterns reveal specific neural mechanisms. During the Discovery stage, students' planning and creative ideation (mean rating 4.5) reflect executive function engagement in the prefrontal cortex, which is essential for creative problem solving. During the Application stage, the highest engagement rating (4.8) corresponds to multisensory integration and procedural learning, where visual, tactile,

and kinesthetic inputs are processed simultaneously. During the Communication stage (4.7), memory consolidation occurs through retrieval practice and social cognition.

These findings demonstrate that STEAM project-based learning through solar system diorama construction significantly supports deep learning through specific neurocognitive pathways. From a neuropsychological perspective, the effectiveness can be explained through multisensory and context-rich learning experiences that engage distributed neural networks. When students assemble and decorate dioramas, they process visual, auditory, tactile, and kinesthetic information simultaneously. Activation of multiple sensory areas strengthens neural connections through long-term potentiation, making memory traces more robust and accessible (Suryanti et al., 2024).

The elaborative encoding processes during Discovery and Application stages play crucial roles in deep learning. When students discuss planetary proportions or resolve representation challenges, they engage in deep information processing within the prefrontal cortex, responsible for executive functions including planning and problem-solving. These higher-order cognitive activities transfer information from short-term to long-term memory in the hippocampus and association cortices (Daugirdiene et al., 2024). Observed engagement ratings of 4.5 and 4.8 for these stages provide behavioral evidence of prefrontal engagement.

The emotional and social dimensions also significantly contribute to neurocognitive effectiveness. Enthusiasm and enjoyment observed throughout the project trigger dopamine release in reward centers, enhancing motivation and facilitating synaptic plasticity. Social interactions during group work activate brain networks supporting social cognition, strengthening learning through resonance and empathy mechanisms.

Qualitative themes further supported the neuropsychological analysis. As shown in Table 3 (presented earlier), the themes of Emotional Resonance and Metacognitive Awareness provided phenomenological evidence of the neural processes at work. Students expressed pride and excitement (emotional resonance), which aligns with dopaminergic reward circuit activation. One student stated, "I was so proud when my parents saw our diorama. I explained everything to them." Regarding metacognitive awareness, a student explained, "At first I didn't understand why planets orbit the sun, but building the model made it click," reflecting conscious awareness of their own learning process, which engages prefrontal monitoring networks. These qualitative findings confirm that the diorama project activates not only cognitive but also emotional and social neural systems, creating a richer and more durable learning experience.

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2. Discussion

a. Deep Learning Aspects

Our results identified five specific deep learning aspects that were significantly strengthened by the STEAM diorama project: conceptual understanding, sustained engagement, collaborative reasoning, creative problem solving, and science self-efficacy (see Table 1). Each aspect improved through distinct but interrelated mechanisms. Conceptual understanding (mean gain from 3.24 to 4.56, d=1.89) was enhanced by the physical manipulation of materials during the Application stage, which activated multisensory integration and procedural learning pathways (Daugirdiene et al., 2024). Sustained engagement (3.29 to 4.74, d=2.18) was fostered by the hands on, enjoyable nature of the project, supported by emotional resonance as revealed in student interviews (Table 2). Collaborative reasoning (3.18 to 4.62, d=2.04) was strengthened through peer negotiation and shared decision making during the Discovery and Application stages, reflecting social cognition mechanisms (Candela-Leal et al., 2025). Creative problem solving (3.11 to 4.58, d=2.08) was developed when students designed and refined their diorama sketches, engaging executive function and cognitive flexibility (Son & Kim, 2025). Finally, science self-efficacy (3.22 to 4.49, d=1.82) grew from the successful completion and public exhibition of the diorama, which provided positive feedback and social recognition.

Our finding that collaborative reasoning improved significantly (d=2.04) aligns with previous research on project-based learning in STEAM contexts. Similar gains in collaborative competence among elementary students engaged in hands-on science projects. However, our study extends this by demonstrating that the neural mechanisms underlying social cognition—particularly theory of mind and empathy—are activated during group diorama construction, as reflected in student interviews (Table 2).

The improvement in science self-efficacy (d=1.82) is worth noting separately. Self-efficacy, defined as a student's belief in their ability to succeed in science tasks, is closely linked to authentic achievement experiences. In our study, the successful completion of a tangible, visually appealing diorama—followed by public exhibition and positive feedback from teachers and parents—provided exactly such mastery experiences. STEAM project-based learning enhances self-efficacy through creative expression and social recognition, a finding that our qualitative data strongly support (see Table 2, emotional resonance theme).

b. Neuropsychological Aspects

Beyond the specific gains discussed above, the overall effectiveness of the STEAM diorama project can be explained from a neuropsychological perspective through multisensory and context rich learning experiences that engage distributed neural networks. When students assemble and decorate dioramas, they process visual, auditory, tactile, and kinesthetic information simultaneously. Activation of multiple sensory areas strengthens neural connections through long term potentiation, making memory traces more robust and accessible (Clabough, 2025; Thomas, 2024).

The elaborative encoding processes during Discovery and Application stages play crucial roles in deep learning. When students discuss planetary proportions or resolve representation challenges, they engage in deep information processing within the prefrontal cortex, responsible for executive functions including planning and problem-solving. These higher-order cognitive activities transfer information from short-term to long-term memory in the hippocampus and association cortices (Daugirdiene et al., 2024). This elaborative encoding process directly explains the large gains we observed in conceptual understanding and creative problem solving. Recent neuroimaging studies confirm that deep information processing in the prefrontal cortex during hands-on tasks enhances both semantic memory formation and cognitive flexibility (Leikin et al., 2025; Ribeiro et al., 2025). Observed engagement ratings of 4.5 and 4.8 for these stages provide behavioral evidence of prefrontal engagement (see Table 3 and Figure 4).

The emotional and social dimensions also significantly contribute to neurocognitive effectiveness. Enthusiasm and enjoyment observed throughout the project trigger dopamine release in reward centers, enhancing motivation and facilitating synaptic plasticity. Social interactions during group work activate brain networks supporting social cognition, strengthening learning through resonance and empathy mechanisms.

D. Conclusion

This study had two main goals. First, we wanted to see whether a STEAM based solar system diorama project could strengthen five specific aspects of deep learning in elementary science: conceptual understanding, sustained engagement, collaborative

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reasoning, creative problem solving, and science self-efficacy. Second, we aimed to explain from a neuropsychological perspective how such a project might work.

The results clearly show that both goals were achieved. All five deep learning aspects improved significantly from pre-test to post-test, with large effect sizes (Cohen's d ranging from 1.82 to 2.18). The qualitative findings also confirmed that students experienced embodied understanding, collaborative cognition, and emotional resonance. Moreover, the neuropsychological analysis revealed that the diorama project engaged multisensory, emotional, and social neurocognitive processes, which helps explain why the improvements happened.

The five-stage Laboy—Rush PjBL STEAM model proved to be well aligned with how the brain naturally learns. The sequence from Reflection to Communication mirrored the brain's learning cycle—schema activation, encoding, elaborative processing, consolidation, and retrieval practice—which likely contributed to the unusually large effect sizes we observed.

These findings have practical implications. The diorama project offers a low-cost, hands-on strategy for elementary teachers to foster deep learning. For teacher training, integrating basic neuroscience literacy can help educators resist neuromyths and design evidence-based lessons.

However, this study also has several limitations that should be acknowledged. First, the intervention lasted only eight weeks, so we cannot be sure how long the learning gains will be retained. Second, the sample came from a single elementary school in West Jakarta, which limits how far we can generalize the findings to other schools or regions. Third, our neuropsychological analysis relied on behavioral observations and self-reported questionnaires rather than direct neuroimaging or physiological measures (such as EEG or fMRI). While these methods are practical and informative for classroom research, they cannot directly confirm neural activation patterns. Future studies should address these limitations by extending the intervention period, replicating the study across more diverse schools, and incorporating neuroimaging techniques where feasible.

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