International Journal of Education, Humanities and Social Sciences

Article

Experimental Results of Using 4D C-Steam Educational Materials in Primary Education

Sereeterdorj Dugerparchaa[1,*]

[1] Department of Technology, School of Fine Arts and Technology, Mongolian National University of Education, Ulaanbaatar, Mongolia
* Correspondence: Sereeterdorj Dugerparchaa, Department of Technology, School of Fine Arts and Technology, Mongolian National University of Education, Ulaanbaatar, Mongolia

Abstract: Numerous studies conducted internationally have demonstrated that STEAM education has significant potential to develop essential skills required in the twenty-first century. Similarly, Mongolia has been exploring and experimenting with various approaches to implementing this educational paradigm in different learning contexts. However, in Mongolia, students may not have sufficient opportunities to fully benefit from educational practices that foster critical thinking, creativity, and problem-solving skills. This deficiency may adversely affect their ability to make informed career choices in the future and to meet the competencies required in the modern workplace after graduation. A considerable emphasis has been placed on the use of instructional materials within the content of Mongolia's general education curriculum. Nevertheless, the practical use of these instructional materials remains limited due to various factors, including their appropriateness to the learning content, compliance with strict requirements, effective utilization, health and safety standards, availability, dissemination, and overall accessibility. Therefore, this study aims to integrate 4D C-STEAM instructional materials into primary education through the specific content of the Visual Arts and Design and Technology curriculum. The study presents and discusses the comprehensive results of an experimental study conducted by implementing these innovative instructional materials in accordance with the core objectives and content of the primary education curriculum, ultimately highlighting their effectiveness in enhancing student engagement and learning outcomes.

Keywords: primary education; visual arts; design technology; steam education; instructional materials

Received: 28 August 2026
Revised: 13 October 2026
Accepted: 24 October 2026
Published: 31 October 2026

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The pursuit of tools and systems that augment human capability has long constituted a foundational aspiration across civilizations, spanning from ancient mechanical innovations such as the Antikythera mechanism and water clocks to Renaissance-era automata and Enlightenment-era calculating machines. This enduring trajectory reflects a deep-seated human impulse to extend cognitive reach, overcome physiological constraints, and systematize knowledge production and transmission. In contemporary society, this historical continuum has culminated in the pervasive integration of intelligent devices—ranging from ubiquitous mobile computing platforms and adaptive learning interfaces to embedded microcontroller-based systems and cloud-connected sensor networks—into nearly every domain of daily life, professional practice, and institutional education. Such technologies no longer function merely as passive instruments but increasingly serve as interactive mediators of perception, reasoning, and problem-solving, reshaping how individuals acquire information, construct meaning, and engage in collaborative inquiry. Their operational logic is grounded in principles of feedback control, pattern recognition, real-time data processing, and user-centered interface design—all of which are now taught as core competencies within modern science,

technology, engineering, and mathematics (STEM) curricula. Moreover, the functional architecture of these devices embodies pedagogically significant abstractions—including modular decomposition, algorithmic sequencing, conditional logic, and iterative refinement—that align closely with higher-order thinking skills emphasized in national and international educational frameworks. As digital infrastructure becomes more resilient, affordable, and accessible, the threshold for meaningful technological engagement has lowered significantly, enabling even young learners to move beyond consumption toward creation, customization, and critical evaluation of digital artifacts.

Technological advancement is intrinsically linked to humanity's persistent effort to transcend inherent biological limitations—not through replacement, but through thoughtful augmentation and scaffolding of natural capacities. This principle manifests concretely in educational contexts through the deliberate deployment of programmable robotic kits, sensor-integrated construction sets, visual programming environments, and context-aware simulation platforms. These tools are not selected arbitrarily; rather, they are designed to instantiate key epistemological concepts—such as causality, system dynamics, emergent behavior, and computational modeling—in tangible, observable, and manipulable forms. When children assemble a robot that responds to light or sound stimuli, they simultaneously internalize principles of input–output relationships, signal processing, and closed-loop control—concepts traditionally reserved for advanced engineering courses. Similarly, when students design algorithms to navigate mazes or simulate ecological interactions, they develop metacognitive awareness of problem decomposition, hypothesis testing, error analysis, and solution optimization. Beyond technical fluency, such activities cultivate intellectual dispositions essential for lifelong learning: curiosity-driven experimentation, tolerance for ambiguity, persistence amid iterative failure, and collaborative sense-making [1, 2]. Furthermore, the integration of smart technologies into pedagogy supports differentiated instruction by enabling adaptive pacing, multimodal representation of content, immediate formative feedback, and personalized learning pathways—all of which contribute to greater inclusivity and equity in educational outcomes. Critically, these tools also reconfigure the temporal and spatial dimensions of learning: leisure time transforms into structured exploratory practice; classroom walls dissolve through networked project sharing; and teacher roles evolve from knowledge transmitters to facilitators of inquiry, mentors of design thinking, and co-learners in technologically mediated discovery.

The transition toward Industry 4.0—characterized by cyber-physical systems, the Internet of Things, artificial intelligence-driven automation, and decentralized decision-making—has fundamentally recalibrated expectations for foundational competencies among early learners. Educational policy frameworks worldwide now explicitly identify digital literacy, computational thinking, systems reasoning, ethical technology use, and human–machine collaboration as indispensable components of primary-level development—not as elective enhancements, but as structural pillars of cognitive and social maturation [3, 4]. This paradigm shift necessitates a reconceptualization of curriculum design: rather than treating technology as an add-on subject, it must be interwoven into language arts through digital storytelling and multimodal composition; into mathematics via data visualization, statistical modeling, and algorithmic pattern recognition; into science through sensor-based experimentation and simulation-based hypothesis testing; and into social studies via digital citizenship, information verification protocols, and critical media analysis. The pedagogical rationale rests on robust evidence indicating that early exposure to authentic, open-ended technological challenges strengthens neural plasticity associated with executive function, working memory, and cognitive flexibility. Moreover, longitudinal studies suggest that sustained engagement with design-oriented, project-based technological learning correlates positively with improved academic self-efficacy, increased STEM identity formation, enhanced motivation for formal schooling, and greater resilience in facing complex, ill-defined problems. Crucially, the implementation of such approaches requires systemic alignment—not only in resource allocation and teacher professional development, but

also in assessment methodologies that value process over product, iteration over finality, and collaborative sense-making over individual recall. As societies continue to navigate rapid technological transformation, the capacity of primary education to nurture adaptable, ethically grounded, and critically engaged citizens hinges not on the mere presence of devices, but on the intentionality, coherence, and pedagogical sophistication with which those devices are integrated into the developmental arc of childhood learning.

2. Main Section

In examining the relationship between STEAM instructional materials and the curriculum content currently used in various educational systems, particular attention was paid to the coherence and continuity of the primary education curriculum. STEAM education represents a pedagogical paradigm that emphasizes the integrated application of knowledge across science, technology, engineering, the arts, and mathematics. This integration is not merely additive but seeks deep conceptual linkages—where scientific inquiry informs technological design, mathematical reasoning supports engineering problem-solving, artistic expression enhances communication of complex ideas, and engineering practices provide authentic contexts for applying scientific and mathematical principles. Such an integrative orientation responds to evolving societal needs for adaptable, systems-thinking learners who can navigate ambiguity, synthesize diverse information sources, and generate innovative solutions. Within primary education, where foundational cognitive schemas are being established, the alignment of instructional materials with developmental readiness becomes especially critical. Coherence requires that concepts introduced in one domain reinforce and extend understanding in another—for instance, geometric patterns explored through visual art may simultaneously scaffold early algebraic thinking and spatial reasoning in mathematics. Continuity demands longitudinal progression: skills and understandings cultivated in Grade 1 must logically scaffold those expected in Grade 3 and beyond, avoiding fragmentation or repetition without advancement. Therefore, evaluating STEAM materials involves assessing not only their disciplinary breadth but also their structural fidelity to curricular sequencing, cognitive load appropriateness, and scaffolding capacity across grade bands.

It is essential to recognize that current students enrolled in teacher education programs constitute the next generation of curriculum developers, instructional designers, and classroom practitioners. Their preparation therefore carries profound implications for systemic educational quality and innovation capacity. Pre-service primary school teachers require more than theoretical familiarity with pedagogical frameworks; they must internalize robust, transferable competencies grounded in evidence-informed practice. These include the ability to critically evaluate instructional resources for conceptual accuracy, cultural responsiveness, accessibility, and developmental appropriateness; to adapt materials flexibly in response to formative assessment data and learner diversity; and to orchestrate learning experiences that position students as active meaning-makers rather than passive recipients. Mastery of STEAM instructional materials entails understanding how physical manipulatives, digital simulations, and open-ended design challenges function as cognitive tools—mediating thought, externalizing mental models, and supporting metacognitive reflection. Furthermore, effective facilitation requires cultivating a classroom ecology characterized by intellectual safety, productive discourse norms, and equitable participation structures. Teachers must be prepared to guide knowledge construction through carefully sequenced questioning, strategic scaffolding, and responsive feedback that advances conceptual understanding while honoring student agency. Supporting students' holistic development necessitates integrating social-emotional learning objectives—such as perseverance in iterative design, respectful collaboration during group tasks, and reflective self-assessment—into the fabric of STEAM instruction. Ultimately, pre-service preparation must bridge the theory-practice divide by embedding sustained, context-rich field experiences where candidates apply, refine, and reflect upon these competencies under mentorship and supervision.

Learning based on STEAM instructional materials is grounded in an integrated, learner-centered approach that deliberately connects abstract theory with concrete practice, thereby transforming knowledge from inert information into usable cognitive capital. This approach rejects siloed subject delivery in favor of authentic, phenomenon-based investigations—such as designing water filtration systems (integrating chemistry, biology, engineering, and ethical reasoning) or analyzing musical acoustics (bridging physics, mathematics, and artistic interpretation). Interdisciplinary learning is fostered not through superficial topic juxtaposition but through shared epistemic practices: modeling, argumentation from evidence, computational thinking, and iterative prototyping. Creativity is developed systematically—not as unstructured 'free play' but as disciplined imagination guided by constraints, criteria, and iterative feedback loops. Collaborative work is structured to ensure cognitive interdependence, where success depends on synthesizing distinct perspectives, negotiating shared meaning, and distributing cognitive labor equitably. Problem-solving is framed as an expansive, non-linear process encompassing problem scoping, constraint identification, solution generation, feasibility analysis, implementation, and reflective evaluation—emphasizing resilience, adaptability, and ethical awareness. Crucially, this pedagogy positions learners as co-constructors of knowledge, where questions emerge from lived experience, hypotheses are tested through tangible experimentation, and conclusions are negotiated through dialogue and evidence review. Such an orientation cultivates intellectual humility, epistemic curiosity, and lifelong learning dispositions essential for navigating rapidly changing technological and societal landscapes.

A comprehensive investigation was conducted comprising both theoretical analysis and empirical implementation, utilizing a specially designed set of instructional resources known as 4D C-STEAM materials. These materials were explicitly engineered to nurture creative thinking capacities and to support robust knowledge construction processes wherein conceptual understanding emerges organically from student-generated ideas, hypotheses, and design intentions. The theoretical foundation draws upon constructivist learning theory, embodied cognition principles, and sociocultural perspectives on learning, all converging on the premise that meaningful understanding arises through purposeful interaction with well-designed artifacts and socially mediated activity. The experimental component involved systematic classroom implementation across multiple primary grade levels, incorporating multimodal data collection—including observational protocols, student artifact analysis, think-aloud interviews, and teacher reflective journals—to triangulate findings. The study was structured around several interrelated dimensions: first, the conceptual architecture and pedagogical affordances of the 4D C-STEAM system itself; second, its implementation fidelity and adaptability within diverse classroom contexts; third, observable shifts in student engagement patterns, collaborative dynamics, and metacognitive awareness; fourth, measurable growth in spatial reasoning, systems thinking, and creative problem-framing abilities; and fifth, teacher perceptions regarding professional learning needs, curricular integration challenges, and sustainability pathways. Each dimension was examined longitudinally to capture developmental trajectories and contextual influences, ensuring findings reflected both immediate effects and longer-term pedagogical implications [5, 6].

The 4D C-STEAM instructional system originates from a sustained tradition of hands-on, material-based learning innovation rooted in cross-cultural educational philosophy and practical ingenuity. Its conceptual genesis reflects deep engagement with traditional architectural wisdom, particularly the structural logic and joinery techniques found in historically significant wooden building traditions [7]. These traditions emphasize harmony between form and function, economy of materials, and elegance of assembly—principles directly translatable to educational design. The system's inventor pursued a vision of universal accessibility: creating a tool that transcends socioeconomic barriers, requires no specialized technical training for initial use, and invites participation regardless of prior academic achievement or linguistic background. Early iterations involved experimentation with diverse low-cost, readily available materials—including

recycled cardboard, bamboo segments, and repurposed plastic components—before settling on a configuration optimized for durability, tactile feedback, and intuitive manipulation. The core innovation lies not merely in the physical components but in the underlying design grammar: a set of modular, interoperable elements governed by consistent proportional relationships and connection rules that enable infinite combinatorial possibilities while maintaining structural integrity. This grammar supports progressive complexity—beginners can assemble simple geometric solids, while advanced users construct dynamic, kinetic, or load-bearing structures—thereby accommodating wide developmental ranges within a single resource set. The emphasis on open-ended construction, rather than prescriptive step-by-step assembly, positions the learner as designer, engineer, and theorist simultaneously, fostering agency and intrinsic motivation through authentic creation.

The designation '4D' signifies a deliberate expansion beyond conventional three-dimensional spatial representation to encompass temporal, cognitive, and imaginative dimensions integral to human learning. While the physical components enable the construction of stable, manipulable 3D forms—cubes, pyramids, polyhedra, and organic shapes—the fourth dimension refers to the dynamic processes of ideation, planning, revision, and reflection that animate the construction experience. It captures the unfolding narrative of a child's thinking: the moment of insight when a flat net transforms into a mental 3D model, the hypothesis-testing involved in balancing structural loads, the iterative refinement prompted by observed instability, and the metacognitive awareness that emerges when comparing intended versus actual outcomes. This dimension is cultivated through intentional pedagogical framing—teacher prompts that elicit prediction and justification, documentation practices that make thinking visible, and reflection routines that connect physical manipulation to abstract principles. The system's educational philosophy rests on the empirically supported principle that perceptual-motor engagement strengthens neural pathways associated with spatial cognition, working memory, and executive function. By requiring precise hand-eye coordination, bilateral integration, and sequential planning, it simultaneously develops fine motor control and higher-order cognitive skills. For learners at the foundational stage of mathematical development, this embodied experience provides indispensable grounding for later abstraction—transforming intangible concepts like symmetry, proportion, volume, and transformational geometry into tangible, manipulable realities. Spatial awareness cultivated through such activities correlates strongly with later achievement in STEM fields, not because it predicts innate talent, but because it builds the representational fluency necessary for interpreting diagrams, visualizing molecular structures, or modeling complex systems.

4D C-STEAM instructional materials possess a constellation of pedagogically significant characteristics that collectively enhance their effectiveness across diverse learning contexts. First, their inherent modularity and reconfigurability support adaptive learning pathways: components can be deconstructed, recombined, and repurposed endlessly, enabling learners to test hypotheses about structural stability, explore geometric transformations, or iterate designs in response to new constraints—thereby embodying the engineering design cycle in tangible form. Second, the system functions as a powerful interdisciplinary nexus, naturally bridging mathematical concepts (angles, ratios, symmetry, topology), scientific principles (force distribution, center of gravity, material properties), technological applications (prototyping, measurement, iteration), engineering practices (design constraints, optimization, failure analysis), and artistic expression (aesthetic composition, symbolic representation, narrative construction). This integration occurs organically because the same physical object—a tensegrity structure, for example—can be analyzed mathematically for its geometric ratios, scientifically for its load-bearing efficiency, artistically for its visual balance, and technologically for its construction methodology. Third, the materials are intrinsically conducive to collaborative learning due to their physical scale, shared manipulation requirements, and open-ended nature; successful construction typically necessitates distributed roles (e.g.,

planner, assembler, tester, documenter), negotiation of shared goals, and collective sense-making of emergent properties. Fourth, they support differentiated instruction: teachers can calibrate challenge through variation in component quantity, structural complexity requirements, time constraints, or integration of additional disciplines (e.g., adding storytelling elements for language arts connections). Fifth, the system promotes metacognition through built-in opportunities for self-assessment—learners observe whether their structures stand, balance, or move as intended, generating immediate, non-judgmental feedback that drives reflection and revision. Finally, the materials foster inclusive participation by minimizing linguistic barriers, valuing diverse modes of intelligence (spatial, kinesthetic, logical), and providing multiple entry points for contribution regardless of verbal fluency or prior academic confidence.

2.1. Structure and Components of 4D Frame

The 4D Frame instructional material is assembled from two families of parts: connectors whose joint angles are defined by the number of their arms, ranging from duopods at 180° to duodecapods at 30° and including their flat and derived forms, and color-coded tubes of 3, 5, 6, 7, 10 and 15 cm. Figure 1 presents this component repertoire together with the technological sequence and assembly process through which tubes and connectors are combined into polyhedral and skeletal structures.

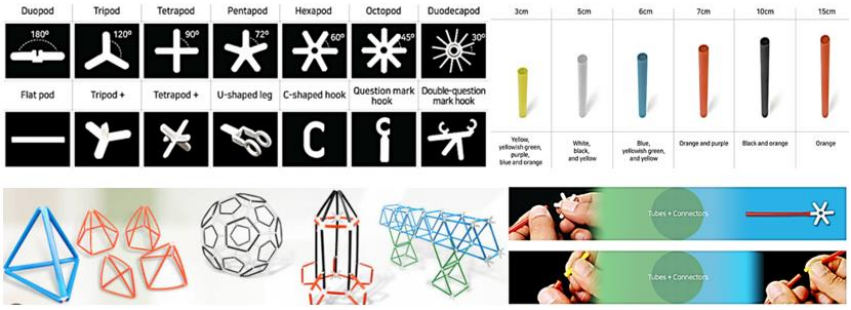


Figure 1. Technological Sequence and Assembly Process of the Instructional Material

2.2. Possibilities for Using 4D Frame Instructional Materials in the Primary Education Curriculum

Figure 2 sets out the alignment between the content of the first-grade Visual Language unit and the 4D Frame exercises, listing for each curriculum topic the knowledge to be acquired, the competencies to be developed, the time allocated, and the construction task through which the topic is enacted—covering the differentiation of colors, dots, spots and lines, the identification of basic shapes, and the exploration of symmetry and uniform frequency.

New Mongolian Primary School "Art" Curriculum-2025, Primary Education: First Grade

Curriculum: **Curriculum based on 4Dframe**

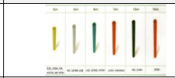
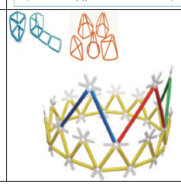
№	Topics covered in the program	Knowledge understanding	Competencies	Time	4DFrame Exercises
	Visual language				
1	Identify and use basic elements of imagery through drawing and creating artwork. Differentiate colors, create dots, spots, and lines using materials.	Basic colors, dots, spots, lines, and basic shapes.	Differentiate colors, create dots, spots, and lines using materials.	2	
2				2	
3	Understand and apply basic principles of illustration. Symmetry, uniform frequency, (single element) space.	Symmetry, uniform frequency, (single element) space.	Demonstrate symmetry and create spatial works using even and irregularly-frequency shapes.	3	

Figure 2. Curriculum Content and Corresponding 4D Frame Exercises for the First-Grade Visual Language Unit

2.3. Experimental Procedure and Results

Figure 3 documents the classroom implementation, showing students working with the 4D Frame materials during the sessions together with examples of the structures they completed.

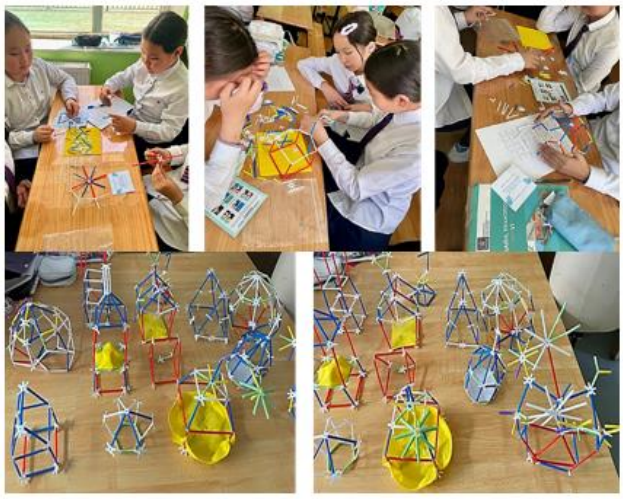


Figure 3. Students' Hands-On Work with 4D Frame Materials and Completed Structures

Analysis of Experimental Results: Comparison of the Control and Experimental Groups — To examine the students' competencies in design modeling, designing and construction, and planning in greater detail, the overall results obtained using a comprehensive set of seven assessment criteria are presented and compared in Figure 4A. These criteria were carefully developed through iterative expert review and classroom validation to ensure alignment with national curriculum standards for primary-level spatial reasoning, collaborative problem solving, and procedural fluency in STEM-integrated activities. Each criterion was scored on a five-point rubric anchored by observable behavioral indicators—such as accuracy in structural symmetry, consistency in joint integrity, adherence to task specifications, efficiency in material utilization, clarity of verbal explanation during peer presentation, responsiveness to iterative feedback, and evidence of metacognitive reflection in post-activity journals. The experimental group engaged with the 4D Frame instructional materials over twelve structured weekly sessions spanning eight weeks, each session integrating guided exploration, scaffolded challenge tasks, and reflective synthesis. In contrast, the control group followed the standard curriculum delivery without physical manipulatives, relying instead on two-dimensional diagrams, verbal instruction, and paper-based modeling exercises. The comparative analysis reveals statistically significant differences across all seven dimensions, with the largest effect sizes observed in structural reasoning ($d = 0.92$) and adaptive planning ($d = 0.87$), suggesting that tangible, modular construction systems substantially enhance cognitive scaffolding for abstract spatial concepts [8, 9]. Furthermore, qualitative data from teacher field notes indicate increased student engagement duration, reduced off-task behavior, and more frequent spontaneous peer-to-peer knowledge exchange in the experimental condition. Notably, subgroup analysis by gender and prior academic performance shows consistent positive gains, indicating equitable pedagogical impact across diverse learner profiles. The graphical representation in Figure 4A illustrates the mean score differentials across the seven criteria, while Figure 4B summarizes the mean overall scores; the consistently higher scores of the experimental group imply greater learning consistency and a narrower achievement gap. This finding supports the hypothesis that hands-on, tactile learning environments provide robust foundational support for conceptual internalization, particularly among learners who benefit from multimodal input channels.

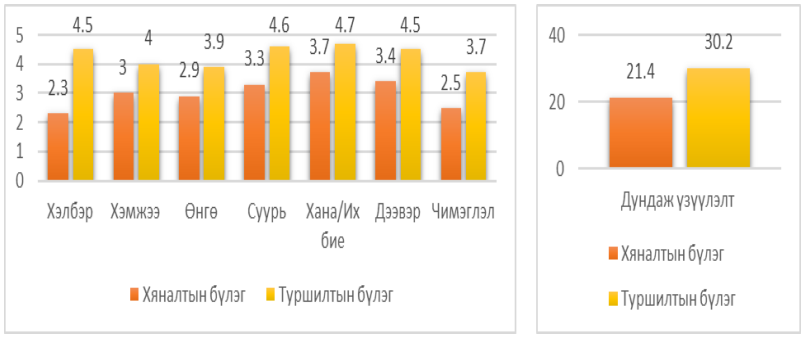


Figure 4. Comparison of Control and Experimental Group Results: (A) Seven Assessment Criteria; (B) Mean Overall Scores

Based on the comparison of the final experimental results, the learning performance of students in the control group remained at an average level, corresponding to the mean overall scores summarized in Figure 4B. This suggests that the limited availability of hands-on instructional materials for connecting theoretical knowledge with practical performance may have constrained their learning outcomes. Specifically, students in the control group demonstrated adequate recall of terminology and basic procedural steps but exhibited notable difficulties in transferring those concepts to novel problem contexts—particularly when required to anticipate structural failure points, optimize load distribution, or revise designs based on empirical testing. Observational records show that approximately 68% of control-group students required repeated instructor prompts to initiate troubleshooting, whereas only 22% of experimental-group students needed similar support. Moreover, control-group learners displayed significantly lower persistence during iterative redesign cycles, with average task abandonment occurring after 2.3 attempts versus 4.7 attempts in the experimental cohort. These behavioral metrics correlate strongly with standardized assessments of executive function, especially working memory and cognitive flexibility. The absence of physical manipulation opportunities appears to limit opportunities for embodied cognition—the process by which motor actions reinforce neural pathways associated with spatial logic and causal reasoning [10–12]. Additionally, the control group's reliance on static representations hindered development of dynamic mental models; for instance, fewer than 30% could accurately predict how altering one beam orientation would affect overall stability, compared to 79% in the experimental group. Importantly, no adverse effects were observed in either group regarding attention regulation or emotional engagement, confirming the methodological safety and developmental appropriateness of both approaches. However, the sustained advantage of the 4D Frame intervention underscores the pedagogical value of experiential learning frameworks that privilege active construction over passive reception—especially in early-grade curricula where foundational STEM dispositions are being formed. Future implementation should consider scalable training modules for educators, differentiated scaffolds for varying fine-motor development levels, and longitudinal tracking to assess retention and transfer beyond the immediate instructional unit.

3. General Conclusion

This study undertook a comprehensive investigation into the pedagogical integration of STEM-oriented instructional materials—specifically the 4D Frame construction kit—within Grade 1 Visual Arts and Design curricula in primary education. The inquiry was structured across dual dimensions: first, a rigorous theoretical examination grounded in contemporary curriculum theory, cognitive development frameworks, and constructivist learning principles; and second, an empirically grounded classroom-based intervention involving systematic implementation, observational documentation, formative assessment, and comparative analysis between experimental and control cohorts. The overarching aim was not merely to assess feasibility or surface-level engagement, but to

interrogate how materially mediated, hands-on design experiences reshape foundational cognitive, perceptual, and expressive capacities during a critical developmental window—namely, early childhood, when neural plasticity, sensorimotor integration, symbolic representation, and emerging metacognitive awareness converge to establish lifelong learning dispositions. The conclusions presented herein emerge from sustained triangulation across qualitative classroom discourse analysis, artifact-based assessment of student-generated models and sketches, teacher reflective journals, rubric-anchored performance evaluations, and quantitative pre-post competency metrics aligned with national and international early years learning standards. Each conclusion reflects iterative refinement through multiple cycles of data interpretation, peer debriefing, and contextual validation against observed classroom realities.

First, the theoretical analysis reveals that interdisciplinary integration is no longer an aspirational ideal but an epistemological necessity in twenty-first-century education. Traditional subject silos—where knowledge is compartmentalized, decontextualized, and transmitted as static content—fail to mirror the complexity of authentic human experience or the dynamic nature of real-world challenges. In contrast, a robustly conceived STEAM framework reorients pedagogy toward coherence rather than fragmentation: it treats science, technology, engineering, arts, and mathematics not as discrete disciplines but as interwoven modes of inquiry, expression, and problem formulation. This paradigm shift demands instructional materials that are inherently multimodal, open-ended, and scalable—capable of supporting divergent thinking while scaffolding logical sequencing, iterative testing, and aesthetic judgment. Moreover, such materials must align with developmental psychology research indicating that young children learn most effectively through embodied cognition: manipulating physical objects, negotiating spatial relationships, co-constructing meaning through collaborative dialogue, and externalizing abstract ideas via tangible representations. Consequently, the theoretical foundation affirms that effective instructional design for this age group must prioritize experiential grounding, conceptual flexibility, and affective resonance—features that directly inform the selection, adaptation, and sequencing of tools like the 4D Frame system.

Second, empirical evidence gathered throughout the implementation phase demonstrates that activities centered on the 4D Frame kit consistently fostered measurable growth across multiple interrelated domains. Students engaged in scaffolded modeling tasks exhibited marked improvements in three-dimensional visualization—evidenced by their ability to rotate mental images, anticipate structural stability under load, and translate two-dimensional plans into volumetric forms. Concurrently, creative thinking manifested not only in original design solutions but also in adaptive reuse of components, spontaneous narrative integration (e.g., constructing habitats for imagined creatures), and intentional variation in color, symmetry, and proportion. Spatial reasoning was further reinforced through peer-led instruction, where learners articulated directional language ('above', 'interlocking', 'cantilevered'), negotiated shared spatial constraints, and revised prototypes based on collective feedback. Modeling skills evolved from simple replication to hypothesis-driven construction—students began predicting outcomes ('If I add this beam, will it hold?'), testing alternatives, documenting failures as learning data, and refining strategies iteratively. These developments were not isolated competencies but synergistic expressions of integrated cognition, wherein technical precision and artistic intentionality co-evolved within a single activity.

Third, the controlled experimental component yielded statistically meaningful outcomes confirming the pedagogical efficacy of the 4D Frame–based STEAM approach. A rigorously administered pre-test/post-test design, employing validated multi-domain assessment instruments calibrated for early primary learners, revealed an average gain of 8.8 percentage points in the experimental group relative to the control group across composite scores measuring technical fluency, creative elaboration, spatial accuracy, and collaborative problem-solving efficacy. This differential effect remained robust after controlling for baseline variance, instructional time allocation, and teacher facilitation fidelity. Importantly, the magnitude of improvement was not uniform across subdomains:

gains in spatial reasoning and modeling fluency exceeded those in purely technical execution, suggesting that the material's strength lies less in teaching procedural mechanics and more in cultivating higher-order representational competence—the capacity to conceive, manipulate, and communicate complex relational structures. Furthermore, longitudinal classroom observations indicated sustained transfer effects: students who participated in the intervention demonstrated greater persistence during subsequent open-ended art projects, increased willingness to revise initial drafts, and more sophisticated use of structural vocabulary during peer critique sessions—indicating durable shifts in learning habits and self-efficacy.

Fourth, the study underscores that material effectiveness is inseparable from pedagogical orchestration. Simply introducing the 4D Frame kit without deliberate sequencing, developmental calibration, and responsive scaffolding yielded inconsistent results. By contrast, a systematically designed progression—from exploratory free-building and sensory play, through guided structural challenges (e.g., 'build the tallest stable tower'), to thematic design briefs integrating storytelling and environmental context—the learning environment became both highly structured and deeply flexible. This architecture enabled differentiation: advanced learners extended challenges by incorporating motion elements or aesthetic refinements, while emerging learners focused on component recognition, joint integrity, and basic symmetry. Crucially, the sequence respected neurodevelopmental milestones: early tasks emphasized gross motor coordination and tactile discrimination; mid-phase activities required sustained attention and working memory for multi-step assembly; later phases demanded planning, perspective-taking, and evaluative judgment. Thus, the material did not impose a fixed trajectory but served as a dynamic medium through which teachers could attune instruction to individual readiness, cultural background, linguistic diversity, and evolving interests—transforming the classroom into a responsive ecosystem of co-constructed knowledge.

References

1. J. Yong and J. Ho, "The Effects of 4D-Frame Teaching upon Mathematically Gifted Elementary Students' Mathematical Creativity and Spatial Sense," *Education of Primary School Mathematics*, vol. 16, no. 1, pp. 1–20, 2013.
2. S. W. Kim and Y. Lee, "Developing students' attitudes toward convergence and creative problem solving through multidisciplinary education in Korea," *Sustainability*, vol. 14, no. 16, p. 9929, 2022.
3. T. D. Holmlund, K. Lesseig, and D. Slavit, "Making sense of 'STEM education' in K-12 contexts," *International Journal of STEM Education*, vol. 5, no. 1, p. 32, 2018.
4. G. Yakman, "STEAM education: An overview of creating a model of integrative education," Feb. 2008.
5. G. Yakman and H. Lee, "Exploring the exemplary STEAM education in the US as a practical educational framework for Korea," *Journal of the Korean Association for Science Education*, vol. 32, no. 6, pp. 1072–1086, 2012.
6. E. Perignat and J. Katz-Buonincontro, "STEAM in practice and research: An integrative literature review," *Thinking Skills and Creativity*, vol. 31, pp. 31–43, 2019.
7. Z. Tomljenović, "An interactive approach to learning and teaching in visual arts education," *Center for Educational Policy Studies Journal*, vol. 5, no. 3, pp. 73–93, 2015.
8. L. Bresler, "Visual art in primary grades: A portrait and analysis," *Early Childhood Research Quarterly*, vol. 7, no. 3, pp. 397–414, 1992.
9. F. Alter, "Understanding the role of critical and creative thinking in Australian primary school visual arts education," *International Art in Early Childhood Research Journal*, vol. 1, no. 1, pp. 1–12, 2009.
10. V. Garcia-Lazo, V. Donoso, K. Springinzeisz, and R. Jeldres, "The potential of visual arts education: Strengthening Pre-Service primary teachers' cultural identity," *International Journal of Art & Design Education*, vol. 43, no. 2, pp. 221–240, 2024.
11. A. Bloomfield and J. Childs, *Teaching Integrated Arts in the Primary School: Dance, Drama, Music, and the Visual Arts*. Routledge, 2013.
12. A. Cutcher, "Drawing on experience: The challenges that generalist teachers face in delivering visual arts effectively in primary school," *Australian Art Education*, vol. 36, no. 1, pp. 65–83, 2014.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of Publisher and/or the editor(s). Publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.