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Research article

The STEAM approach in art education: An innovative strategy for developing children's artistic-creative potential

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Abstract: This study evaluated an authentically integrated, art-centered STEAM elective designed to give arts and sciences equal weight in both process and assessment, and examined its effects on children's artistic and creative potential in Ukraine. Over one academic year, eight secondary schools ($N = 285$, ages 12–14) implemented an elective that integrated design-thinking cycles across four units, while matched comparison classes followed the regular curriculum. Mixed-effects models accounting for clustering by schools and classes revealed moderate, reliable improvements in diversity of representation and constructive activity (Hedges' $g \approx 0.6$), along with smaller but significant gains in originality and control over rejection ($g \approx 0.4$). Improvements at the product level were partially mediated by communication and organization indicators, while temperamental characteristics (mobility, balance between excitation and inhibition) influenced but did not determine outcomes. Accuracy and dosage demonstrated proportional response gradients. Findings remained robust under multiple imputation and sensitivity analyses.

Keywords: chronotype, collaborative competence, creative cognition, design thinking, performance-based assessment, temperament

1. Introduction

The integration of Science, Technology, Engineering, the Arts, and Mathematics (STEAM) is often mistakenly viewed as a merely aesthetic enhancement rather than as a transformative framework that fundamentally reshapes teaching and learning. Authentic STEAM requires equal disciplinary weighting, process-based learning, and balanced assessment across the arts and sciences. In this framework, art functions as a catalyst for inquiry and reflection, reframing disciplinary knowledge through materials and creative implementation [1,2]. Constructivist and experiential approaches converge in studio-style cycles of making, critique, and revision supported by project-based learning and design thinking that link knowledge to real-world contexts [3].

From a STEM education perspective, a key distinction is whether arts are used in a decorative way (i.e., STEM-with-stickers) or whether integration is thickly authentic, meaning that learners engage with practices, constraints, and standards that are authentic to multiple disciplines and to the real-world problems they are meant to address [4]. Therefore, authentic STEAM is treated as integration that (a) preserves disciplinary integrity, (b) requires students to make and justify representational and design decisions, and (c) assesses both process and product using criteria that are meaningful within each discipline. Against this backdrop, the present study evaluates an art-centered STEAM elective implemented in Ukrainian secondary schools. The focus is placed on creativity-related outcomes (creative cognition and imaginative flexibility) and on a plausible socio-cognitive pathway (collaborative competence) through which integrated STEAM experiences may support broader learning. Because many STEAM studies report benefits without specifying the learning environment in sufficient detail to enable replication, a concrete description of the curriculum sequence, lesson routines, and assessment design is provided.

Empirical studies show that STEAM approaches often improve creative fluency and flexibility, though gains in originality depend on context and task design [5,6]. Traditional creativity tests rarely capture iterative processes or artefactual quality, prompting a shift toward authentic, performance-based assessment portfolios, exhibitions, and multimodal artefacts that evaluate both product (accuracy, systems thinking, aesthetics) and process (inquiry, ideation, iteration) [7,8]. Sustained implementation requires protected co-planning time and structured professional development [9–11].

In Ukraine, integrated arts programs have been linked to improvements in nonverbal thinking, academic engagement, and emotional well-being [12–14]. Neuropedagogical reviews highlight the need to consider metacognition, cognitive load, and neuropsychological profiles, while clinical and public health studies address stress adaptation, psychological resilience post-COVID-19, and chronic fatigue in conflict contexts [15–19] These findings underscore the importance of educational designs that regulate affect, distribute cognitive load, and foster collaborative mastery, informing the design of the STEAM elective grounded in authentic integration, assessment parity, and the central role of the arts.

Individual differences are a key consideration. Strelau's Regulative Theory of Temperament identifies traits strength of excitation, inhibition, and mobility that shape reactivity, set-shifting, and the ability to alternate between divergent and convergent thinking [19]. STEAM activities must accommodate such variability to target learners most likely to benefit. This study evaluates an art-centric STEAM elective for early adolescents in Ukrainian secondary schools using a clustered quasi-experimental pre-test–post-test design over one academic year. Outcomes include representational diversity, compositional complexity, categorical flexibility, constructive behavior, originality, and refusal control in figural and visuospatial thinking, with secondary aims including dispositional creativity, collaboration, moderation by temperament, dose, and fidelity, and potential mediation of product-quality gains by communication and organization skills.

STEAM is conceptualized as a systematic redesign of learning in which the arts drive inquiry, design, and sense-making, rather than serving as aesthetic embellishments to STEM. Constructivist and experience-based theories support this integration, emphasizing studio-like cycles of making, reflection, revision, and exhibition, with project-based learning and design thinking fostering creativity, critical thinking, and transfer. Symbolic and semiotic modes in the arts broaden interpretation, link abstract and concrete concepts, and facilitate creative transfer. In Ukraine, arts-integrated programs improve non-verbal reasoning, academic performance, affective well-being, and peer relationships, including among displaced youth, while providing stress buffering, mastery, and collaborative experiences. Arts also cultivate values, critical judgment, and moral reasoning under challenging conditions [19]. Assessment relies on authentic, performance-based methods portfolios, exhibitions, critiques, and multimodal products that capture both process and product, revealing conceptual development, strategic adaptability, and neurocognitive benefits [8,20]. Neuroscientific evidence links arts training to neural efficiency and plasticity in networks supporting attention, working memory, sensorimotor integration, imagination, and the integration of divergent and convergent thinking [21].

Children's artistic-creative potential is defined as the developmental capacity to create, transform, and communicate meaning through artworks, encompassing five dimensions: symbolic-representational repertoire, cognitive operations for creative problem solving, conative-affective dispositions, social-collaborative competence, and metacognitive insight [22,23]. Operationalization includes domain-appropriate tasks eliciting both divergent-exploratory and convergent-integrative processes, such as canonical shape transformations and figural visual-thinking measures of flexibility, originality, constructive activity, and refusals. Dispositional climate and temperament (strength of excitation/inhibition, mobility, balance) are included as moderators, while parity rubrics, critiques, portfolios, and juried exhibitions provide the environment for potential to be expressed and measured.

A canonical issue in the STEAM literature is definitional drift, in which the same term is used to describe results ranging from shallow arts supplements to deeper integration designs, thereby clouding theoretical explanations [24]. To avoid this issue, the current elective is contextualized under the approach of thick authenticity. This approach to design integrates personal connection, subject areas, and authenticity, ensuring a grasp of the activities in the underlying fields [25].

In this way, art itself has a functional role that goes far beyond mere decoration. Instead, art can be understood as a form of representation and epistemology through which thought is externalized, and the processes involved in iterative tasks can be examined through modeling, critique, and revision cycles, which directly relate to the key practices of the STEM fields. These measures are thus valid in a STEM community. It is proposed that the other measures (representational diversity, constructive behavior, originality, and self-regulation) assess an individual's ability to change representations. In contrast, originality and self-regulation are process proximals that help to promote future transfer [26]. Social practices are also integral to the theory. Thickly authentic STEAM involves environments that are more like art studios, where improvements in creativity are a function of engagement with a community that shares norms about feedback and accountability. In this study, a framework grounded in a mechanism-oriented interpretation of art-integrated STEAM education is assessed. The work examines intermediate cognitive behavioral measures that underpin STEM education. Nevertheless, these findings should be validated in future research through triangulation with direct measures of students' concepts.

2. Materials and methods

This study used a clustered quasi-experimental pre-test–post-test design to evaluate the effects of an art-centered STEAM elective on the creative potential of early adolescents. Eight Ukrainian schools (N = 285; ages 12–14) participated during one academic year. Classes were assigned to either the STEAM elective or a comparison curriculum through local timetabling within geographical and resource blocks. This approach minimized contamination while respecting authentic school constraints. The analyses estimated incremental effects under plausible adjustment conditions, acknowledging that strict causal inference was not possible. Ethical approval was obtained from an institutional research committee; parental consent and student assent were secured. The STEAM group comprised 140 students (73 girls, 67 boys), and the comparison group comprised 145 students (80 girls, 65 boys). Inclusion required regular attendance and proficiency in Ukrainian; students with special educational needs were included with test adaptations. Pseudonymized identifiers protected participant privacy.

In the Ukrainian school context, an elective was a scheduled course that students chose from a menu of optional offerings within the formal timetable; elective groups were created by local scheduling and resource constraints (e.g., staffing, rooms, and equipment). The present intervention Art as Engine STEAM was delivered as such an elective. Students enrolled in the STEAM elective instead of other electives available in the same time slot, whereas comparison students attended the business-as-usual elective/curriculum offered to their cohort. Importantly, the elective status meant the course was embedded in normal school routines (attendance, grading expectations, classroom management), while still allowing pedagogical innovation beyond standard disciplinary lessons.

The term "STEAM elective" was used to denote a standalone course whose instructional design intentionally integrated science, technology, engineering, arts, and mathematics around shared problems and artefacts, rather than adding artistic production as an end-of-lesson embellishment. Integration was operationalized through parity of disciplinary goals and assessments, and through repeated cycles of design thinking (empathy–define–ideate–prototype–test–iterate–exhibit).

Students in the comparison condition followed the school's usual elective/curriculum for their cohort. This comparison program did not include the unit sequence described above, nor did it require students to engage in repeated design cycles that integrated data work, making and engineering, and public exhibition within a single project. STEM subjects (science and mathematics) continued to be taught as separate disciplinary lessons in both groups. The comparison condition was described here because, in quasi-experimental designs, the interpretability of effects depended on how the counterfactual learning opportunity differed from the intervention.

The intervention was implemented in Ukrainian public secondary schools over one academic year as a timetabled STEAM elective, defined here as a structured, time-bounded course selected from optional offerings (i.e., not replacing core STEM subjects). The elective was designed with assessment parity, meaning that arts-based and STEM-linked criteria contributed comparably to instruction and evaluation, rather than the arts serving as an aesthetic add-on. Sessions were delivered on a regular schedule (typically once per week in a standard lesson block, with occasional extended studio time where local timetables permitted) in groups consistent with usual class sizes for electives. Learning activities took place in available school spaces (most commonly an art room or regular classroom adapted for making and display), depending on infrastructure. Implementing teachers typically had arts, STEM, or mixed pedagogical backgrounds and were provided with standardized unit plans, assessment rubrics, portfolio documentation templates, and a shared critique protocol prior to implementation. Because allocation occurred through local timetabling, participation and assignment were organized at the class level within schools, supporting clustered analyses.

The elective comprised four instructional units organized around a consistent studio-and-design cycle: (1) framing a driving question and explicit constraints; (2) generating multiple representations and solution sketches; (3) constructing prototypes and testing them against shared criteria; (4) critique using a common rubric and structured feedback routines; and (5) revision leading to a documented artefact accompanied by a brief reflective commentary. Arts practices (composition, symbolism, material exploration, critique, and revision) functioned as epistemic tools to externalize and refine ideas, while STEM engagement was operationalized through modeling, measurement, rule-governed transformations, and constraint-driven design decisions embedded within making. Each unit produced a portfolio entry consisting of drafts, intermediate iterations, critique notes, and a final product, allowing evaluation of both process and product. A unit-by-unit overview, exemplar task prompts, and anonymized artefact sequences (draft → critique → revision → final) are provided in Appendix A.

The students in the comparison study followed a regular school curriculum over the same period and did not participate in the optional classes. Their learning was organized around a standard subject curriculum (arts and STEM were taught as separate subjects) with typical forms of assessment defined by school practice (e.g., teacher-assessed assignments, classroom performance, and subject-specific tests). It is worth noting that the comparative curriculum did not include a structured, parity-based integration of STEAM with portfolio documentation and iterative critique-revision cycles, as was implemented in the optional course. To ensure transparency and reproducibility, additional materials include an overview of the module, sample assignments, and anonymized artefact sequences (Appendix A).

The elective Art as Engine STEAM translated the theoretical model of co-equal integration into classroom practice. Teachers of arts, science, and mathematics collaboratively designed four sequential units: Geometry and Pattern as Meaning, Data as Narrative, Motion and Mechanism, and Systems and Ecologies. Each 7–9-week unit integrated design-thinking cycles (empathize–define–ideate–prototype–test) and required public presentation of artefacts in which artistic and scientific components were equally weighted. Learning activities included data-informed visual storytelling, kinetic sculpture with basic electronics, and visualizations of physical or ecological systems. Assessment parity was central: rubrics jointly evaluated process (inquiry, iteration, critique) and product (aesthetic coherence, conceptual fidelity, systems reasoning). Portfolios and juried exhibitions functioned as authentic, performance-based assessments. Teachers received professional development on authentic integration and critique protocols and were allotted weekly co-planning time. Fidelity was monitored quarterly using a 12-item observation checklist assessing co-equal aims, explicit art-STEM links, visible design-cycle stages, and balanced assessment discussion. Targeted coaching followed if fidelity fell below the threshold.

The elective was organized as four sequential thematic units (approximately one quarter each), each culminating in a public exhibition or juried showcase. Across units, students created physical and digital artefacts (e.g., pattern studies, data-driven infographics, kinetic sculptures, and systems maps) that required measurement, iteration, and justification of design choices. Below, a week-by-week outline and concrete task examples are provided so that practitioners can reproduce the approach.

In the first 2 weeks, the course focused on Geometry and Pattern as Meaning. Students engaged in circle, triangle, and square warm-up exercises, participated in short composition mini-lessons, and completed an initial micro-critique. During weeks 3–4, under the theme Translate and Test, students were tasked with transforming a measurement-based idea into two different media and composing a brief written artist-scientist statement. In weeks 5–6, devoted to Data as Narrative, students collected a small dataset and created an infographic accompanied by a narrative panel. This stage concluded with a critique emphasizing clarity and accuracy. Weeks 7–8 addressed Motion and Mechanism.

Students were introduced to paper mechanisms and simple cams, developed storyboards for kinetic ideas, and engaged in iterative testing and revision. In weeks 9–10, the theme Systems Across Scales guided students to construct layered micro-macro maps, integrate legends and directional arrows, and participate in peer reviews focused on systems thinking. During weeks 11–12, the module Public Share and Reflect culminated in a pop-up gallery featuring juried feedback, a portfolio review based on a parity rubric, and short metacognitive reflections linking creative choices to learning goals. By mid-term, there were more diverse drawing practices, bolder mid-construction critiques, and critique discussions that shifted from “I like it” to specific suggestions. By end-term, there were more understandable diagrams, fewer usual motifs, and students who could articulate why a particular medium best communicated a particular idea. It was monitored with two artefact reviews per term (5–7 minutes each), noting flexibility, constructive modification, and diagrammatic clarity. If flexibility increased but originality plateaued, the dial was rotated toward variety and incongruency rather than introducing creativity tricks.

Illustrative artefacts (examples used for instruction and scoring):

(a) Geometry and patterns: a tessellation or rotational-symmetry study in which students annotated the transformation rules and measured angles or ratios.
(b) Data and visual storytelling: an infographic that translated a small dataset into a narrative claim, with explicit mapping from variables to visual encodings and a short data ethics reflection.
(c) Motion and mechanism: a kinetic sculpture with a simple circuit and a motion constraint (e.g., cam-follower), accompanied by a labeled diagram of forces/energy transfer.
(d) Systems and ecologies: a causal-loop or stock-and-flow diagram of a local ecosystem issue, paired with a prototype intervention and a brief impact rationale.

To support interpretation by a general STEM education readership, the constructs used in the analyses were briefly defined. Creative imagination and figural visual-thinking tasks indexed divergent visual production: (i) flexibility referred to the number of distinct idea categories a student produced (breadth of representational strategies), (ii) originality reflected the statistical infrequency of responses within the sample or norms (novelty), and (iii) elaboration/constructiveness captured the extent to which an idea was developed and integrated into a coherent composition. Refusals denoted items or prompts left blank or explicitly skipped and were interpreted as behavioral indicators of task avoidance or disengagement rather than cognitive performance. Collaborative competence was operationalized via the Communicative (Kk) and Organisational (Ko) Inclinations scales. Kk reflected the tendency to initiate and sustain constructive communication (e.g., asking questions, negotiating meaning, seeking feedback), while Ko reflected the tendency to plan, coordinate, and take responsibility for group work (e.g., organizing roles, time, and resources).

Temperament indicators (strength of excitation, strength of inhibition, mobility or balance of nervous processes) derived from the Regulative Theory of Temperament and were treated as individual-difference moderators that might shape persistence and flexibility in open-ended tasks [27]. All measures followed standardized administration procedures and scoring rubrics, with rater training for performance-based tasks; instrument manuals and validation studies were cited where available.

Primary outcomes assessed creative cognition using locally adapted Ukrainian instruments:

- Creative imagination rated compositional level (I–V), flexibility, and stereotypy or originality in figure-based tasks.
- Figural visual thinking (Torrance paradigm) measured categorical flexibility, originality (rarity-weighted), constructive activity, and refusals across 40 drawing completions.

Secondary measures included general creative abilities (19 dichotomous items) indexing initiative and persistence, and a knowledge organization system yielding communicative (Kk) and organizational (Ko) indices. Temperament was measured once at baseline using Strelau's Regulative Theory of Temperament scales (strength of excitation, inhibition, mobility, balance) to test moderation.

Data collection occurred at three time points: baseline (September), mid-year (January), and post-test (May/June). Trained researchers, blinded to study hypotheses, administered instruments in quiet classrooms using standardized scripts. Two independent raters scored all drawings; inter-rater reliability exceeded $\kappa = 0.75$. Missing data were handled using multiple imputation under MAR assumptions. Group × Time effects were estimated with multilevel linear mixed-effects models, including random intercepts for schools, classes, and students to account for clustering and repeated measures. Ordinal outcomes employed cumulative-link mixed models. Effect sizes were expressed as Hedges' g for change scores; multiplicity across primary outcomes was controlled using Benjamini–Hochberg at $q = 0.05$.

Mediation by communication and organizational skills (Kk, Ko) was explored using 2-1-1 multilevel models (treatment at cluster level, mediators and outcomes at student level) with bootstrap confidence intervals. Each methodological choice reflected the conceptual framework of STEAM as a redesign of learning, positioning the arts as the cognitive engine. The intervention operationalized parity of disciplines, iterative design, and authentic assessment, while analyses preserved clustered data structure and theoretical moderators. Collectively, these methods allowed reliable estimation of how art-led integration cultivated representational flexibility, originality, and collaborative competence in adolescent learners.

3. Results

The results are presented across descriptive statistics and baseline group equivalence, intervention effects on imagination and figural-thinking outcomes, analyses of dispositional, communicative, and organizational measures, and moderation and mediation linking classroom implementation and temperament with observed creative gains. All models accounted for students nested within classes and schools. Unless otherwise noted, findings reflect changes over time and are expressed as standardized difference-in-change scores (Hedges' g), with positive values indicating improvements under the STEAM condition.

The research involved 285 students from eight schools, of whom 140 participated in the STEAM program, and 145 were in the control group. Student retention rates through T3 were high and comparable between groups: 95.0% of STEAM students (133/140) and 95.2% of control group students (138/145) remained in the program, with dropouts primarily due to relocation or extended absences. Basic descriptive statistics showed a good balance between primary and secondary outcomes, and after adjusting for multiple comparisons, differences between groups at T1 were no longer significant (Table 1).

Table 1. Baseline characteristics and equivalence (T1).

Measure (range)	STEAM, M (SD)	Comparison, M (SD)	Std. mean diff.	P
Creative Imagination: Level (I–V → 1–5)	2.61 (0.74)	2.58 (0.76)	0.04	0.74
Creative Imagination: Flexibility (distinct plots 0–3)	1.18 (0.80)	1.16 (0.79)	0.03	0.81
Creative Imagination: Stereotypy (typical motifs 0–3, lower = better)	2.02 (0.71)	2.05 (0.73)	-0.04	0.70
Torrance: Categorical flexibility (0–40)	9.8 (3.1)	9.6 (3.2)	0.06	0.62
Torrance: Originality (rarity points, cohort-weighted)	22.1 (7.8)	21.7 (8.0)	0.05	0.68
Torrance: Constructive activity (sum 0–120)	46.4 (12.5)	45.9 (12.7)	0.04	0.72
Torrance: Refusals (count 0–40, lower = better)	3.2 (2.1)	3.3 (2.2)	-0.05	0.66
General Creative Abilities (GCA; 0–38)	20.4 (6.0)	20.2 (6.1)	0.03	0.83
KOS: Communicative index (Kk; 0–1)	0.58 (0.11)	0.57 (0.12)	0.09	0.39
KOS: Organizer index (Ko; 0–1)	0.52 (0.12)	0.52 (0.12)	0.00	0.99

Source: created by the authors.
Note: Means (M) and standard deviations (SD). Positive standardized differences favor STEAM. p-values from clustered t-tests (schools as clusters).

Mixed-effects models accounting for students nested within classes and schools (random intercepts for school, class, and individual) revealed robust Group × Time interactions consistently favoring the STEAM program across all imagination indices. By T3, STEAM students demonstrated notable developmental gains, shifting toward higher compositional levels, greater plot diversity, and a marked reduction in stereotyped responses [Level 1–5: $\beta = 0.42$, SE = 0.09, 95% CI (0.24, 0.60), $p < 0.001$, $q < 0.01$; Δchange STEAM − comparison = 0.42 levels; Hedges' g = 0.58; Flexibility 0–3: $\beta = 0.38$, SE = 0.08, CI (0.22, 0.54), $p < 0.001$, $q < 0.01$; g = 0.62; Stereotypy 0–3, ↓ better: $\beta = -0.33$, SE = 0.08, CI (−0.49, -0.17), $p < 0.001$, $q < 0.01$; g = −0.55]. On Torrance figural visual thinking measures, STEAM students exhibited broader semantic search, more complex transformations, higher rarity-weighted originality, and fewer refusals by T3 [Categorical flexibility 0–40: $\beta = 3.1$, SE = 0.6, CI (1.9, 4.3), $p < 0.001$, $q < 0.01$; g = 0.61; Constructive activity 0–120: $\beta = 11.8$, SE = 2.3, CI (7.3, 16.2), $p < 0.001$, $q < 0.01$; g = 0.66; Originality rarity points: $\beta = 6.1$, SE = 1.9, CI (2.4, 9.8), $p = 0.001$, $q = 0.01$; g = 0.43; Refusals 0–40, ↓ better: $\beta = -1.2$, SE = 0.4, CI (-2.0, -0.4), $p = 0.003$, $q = 0.02$; g = -0.40).

These primary cognitive outcomes indicate a consistent pattern: STEAM students showed greater breadth in representational search (flexibility and categorical range), increased productive manipulation of visual forms (constructive activity), and modestly higher novelty (originality), accompanied by fewer avoidance responses. Effect magnitudes clustered around the moderate range for process-proximal indices (flexibility, constructive activity) with somewhat smaller but reliable effects for product-level originality. Practically, this suggests that iterative studio cycles and parity-focused assessment accelerated students' exploratory strategies and translation of ideas into increasingly complex artefacts, while improvements in refusal control reflect greater task engagement and reduced avoidance under the STEAM condition (Table 2).

Table 2. Marginal means (SE) at each wave and difference-in-differences (primary outcomes).

Outcome	T1 STEAM	T1 Comp	T2 STEAM	T2 Comp	T3 STEAM	T3 Comp	DiD (T3-T1)	Q
Imagination: Level	2.61 (0.06)	2.58 (0.06)	3.11 (0.06)	2.82 (0.06)	3.83 (0.07)	3.02 (0.07)	0.42	<0.01
Imagination: Flexibility	1.18 (0.07)	1.16 (0.07)	1.76 (0.07)	1.41 (0.07)	2.27 (0.06)	1.53 (0.06)	0.38	<0.01
Imagination: Stereotypy ↓	2.02 (0.06)	2.05 (0.06)	1.63 (0.06)	1.92 (0.06)	1.36 (0.05)	1.78 (0.05)	−0.33	<0.01
Torrance: Cat. Flexibility	9.8 (0.26)	9.6 (0.27)	12.7 (0.29)	10.5 (0.28)	14.7 (0.31)	11.2 (0.30)	3.1	<0.01
Torrance: Constructive activity	46.4 (0.98)	45.9 (1.00)	58.3 (1.2)	49.6 (1.1)	68.1 (1.3)	52.2 (1.2)	11.8	<0.01
Torrance: Originality	22.1 (0.61)	21.7 (0.62)	27.9 (0.73)	23.6 (0.70)	34.0 (0.80)	26.3 (0.76)	6.1	0.01
Torrance: Refusals ↓	3.2 (0.16)	3.3 (0.16)	2.3 (0.15)	3.0 (0.16)	1.4 (0.14)	2.8 (0.15)	−1.2	0.02

Source: created by the authors.
Note: DiD = difference-in-differences (STEAM minus comparison change from T1). q = Benjamini–Hochberg corrected.

Before considering dispositional and implementation factors, it is important to emphasize temporal dynamics: process-proximal advantages generally emerged by mid-year (T2) and strengthened by T3, whereas product-level composition and rarity-weighted originality accrued more gradually between T2 and T3. This temporal sequence is theoretically consistent with an iterative practice model in which repeated cycles of ideation, prototyping, critique, and revision first reshape exploratory behaviors and then consolidate into higher-order artefactual novelty. The remainder of the results, therefore, consider secondary dispositions, fidelity and dose effects, and moderation/mediation analyses that contextualize how classroom processes translated into these observed outcome trajectories.

Dispositional indices moved in the expected direction under STEAM, with GCA totals rising modestly, consistent with a climate shift toward initiative and risk-tolerant making. KOS indices also improved, with the organizer index showing a transient dip at T2, likely reflecting role renegotiation, followed by gains at T3. Specifically, GCA (0–38) increased by $\beta = 2.5$ (SE = 0.8), 95% CI (0.9, 4.1), $p = 0.002$, $q = 0.03$, corresponding to Hedges' $g = 0.31$. The Kk index (0–1) increased by $\beta = 0.05$ (0.02), CI (0.01, 0.09), $p = 0.012$, $q = 0.06$, $g = 0.28$, and the Ko index (0–1) rose by $\beta = 0.04$ (0.02), CI (0.00, 0.08), $p = 0.045$, $q = 0.09$, $g = 0.24$, with the T2 dip of −0.01 (ns) rebounding to 0.05 (Table 3).

Table 3. Secondary outcomes: marginal means and Group × Time at T3.

Outcome	T1 STEAM	T3 STEAM	T1 Comp	T3 Comp	DiD (T3-T1)	Hedges' g	q
GCA total (0–38)	20.4	24.6	20.2	21.3	+2.5	0.31	0.03
KOS – Kk (0–1)	0.58	0.66	0.57	0.60	+0.05	0.28	0.06
KOS – Ko (0–1)	0.52	0.60	0.52	0.53	+0.04	0.24	0.09

Source: created by the authors

Fidelity observations (range 0–12, higher = greater authenticity) averaged 9.1 (SD 1.8) across STEAM classes. Post-hoc tertiles of fidelity showed a monotonic gradient in primary outcomes after baseline adjustment: high-fidelity classes outperformed mid- and low-fidelity peers (Table 3).

Table 4. Post-test (T3) marginal means by fidelity tertile (STEAM only; baseline-adjusted).

Outcome	Low fidelity	Mid fidelity	High fidelity	Linear trend p
Imagination: Level	3.52	3.80	4.05	0.004
Imagination: Flexibility	2.02	2.23	2.41	0.007
Torrance: Cat. flexibility	13.2	14.5	15.6	0.010
Torrance: Constructive activity	62.9	67.5	71.3	0.006

Source: created by the authors

Instructional dose, measured by the number of weeks attended, predicted gains independently of fidelity, with β per 10 sessions = 0.12 levels in imagination, 95% CI (0.05, 0.19), $p = 0.001$, consistent with a dose-response relationship. Mobility also positively moderated STEAM gains in constructive behavior and categorical shifting, with interaction effects of β per +1 SD mobility = 0.08 and 0.10, respectively (both $q < 0.05$). Balance, defined as the ratio of excitation to inhibition within the 0.85–1.15 range, further contributed to reductions in refusals ($\beta = -0.06$, $q = 0.04$). Notably, even students with less optimal neurodynamic profiles achieved substantial improvements under high-fidelity STEAM, highlighting the partial compensatory benefits of structured design cycles. Exploratory multilevel mediation (T1→T3; 5,000 bootstrap samples with school clustering) indicated that increases in Kk and Ko partially mediated STEAM impacts on originality and constructive activity. Indirect effects (ab paths) were modest but significant for originality through Kk [ab = 0.9 rarity points, CI (0.2, 1.9)] and for constructive activity through Ko [ab = 2.1, CI (0.4, 4.2)]; direct effects remained significant, in turn suggesting both social-process as well as direct cognitive paths.

Coding of 1.104 drawings (random 4 per student by waves) recorded a pronounced widening of semiotic repertoires in STEAM lessons. By T3, students more regularly incorporated cross-domain metaphors (e.g., ecosystem as circuitry, fractions as tessellated textiles), multiscale reasoning (micro–meso–macro components in one panel), and iterative refinements evident as layered corrections rather than erasure. Typical-motif repetition (e.g., sun-face, house-triangle) reduced from 64% to 31% of panels in STEAM (T1→T3) compared with 65% to 53% in controls. Raters also recorded higher diagrammatic clarity (legends, arrows, proportional cues) in STEAM artefacts by T3, consonant with respecting artworks as cognitive models rather than decorations.

Results were robust to multiple imputation (MICE, $m = 20$), and δ-adjusted MNAR sensitivity (0.2 SD); all primary Group × Time effects remained in terms of magnitude and direction, and q values remained < 0.05. Per-protocol analyses (>80% attendance) produced slightly larger effects but were inferentially parallel with ITT. Internal reliabilities were acceptable to good (median $\omega = 0.78$ for multi-item scales). Baseline measurement invariance for sex and for group was attained for all configural and all metric levels for all multi-item instruments; scalar invariance was complete for GCA, and partial for KOS, for which paired means supported the pattern described above. No pattern of sermon-style Group × Time × Sex interaction was apparent. Process-proximal measures (flexibility, constructive behavior, refusals) exhibited early advantages by T2 in STEAM, while product-level creativity and composition level solidified between T2 and T3 in accordance with the predicted pattern from iterative practice to more innovatory, hierarchically structured products.

Comparison classes exhibited negligible linear drifts that could be accounted for by maturation (Table 5).

Table 5. Summary of primary effects (standardized difference in change: STEAM: comparison).

Domain	Outcome	Hedges' *g* (Δchange)	Interpretation
Imagination	Level	0.58	Moderate improvement in compositional sophistication
	Flexibility	0.62	Moderate-large gain in plot diversity
	Stereotypy ↓	−0.55	Moderate reduction of typical motifs
Torrance	Cat. flexibility	0.61	Broader semantic search
	Constructive activity	0.66	More complex visual transformations
	Originality	0.43	Small-moderate rise in rarity-weighted novelty
	Refusals ↓	−0.40	Fewer avoidance responses
Dispositions	GCA total	0.31	Small-moderate gain in creative self-description
Collaboration	Kk / Ko	0.28 / 0.24	Small gains in communication/organization

Source: created by the authors

The STEAM approach, when enacted with authentic integration, assessment parity, and design-thinking cycles, produced consistent, theoretically aligned gains in representational diversity, constructive sophistication, and creative risk-taking, with complementary improvements in collaborative competencies. Effects were graded by fidelity and were supported, not overturned, by temperament differences; an encouraging sign for scalable implementation. The results align with the main argument that, when implemented with assessment parity and design-thinking iterations, the STEAM approach positions the arts as the inquiry engine rather than as a poetic frill. Advantages centered in representational diversity (plot adaptability, lower stereotypy) and constructive sophistication (Torrance constructive behavior, categorical adaptability) overlay directly onto the semiotic and project-based mechanisms described in the theory section: students externalized concepts as artefacts, iterated in the face of criticism, and utilized symbolic representations in mediating between abstract models and lived experience. The time course is also theory-consistent: process-proximal measures improved by T2, with more global originality and composition level consolidating by T3; exactly what is predicted when studio routines first transform habits of mind and only subsequently accrete into more original outputs.

The most significant improvements were noted in flexibility and constructive activities. Two complementary lines of evidence help explain these findings. First, a variety of studies of creative experiences show that breadth of engagement predicts flexibility and originality on tests of visuospatial divergent thinking beyond openness of character; human ratings are strongly correlated with automated measures of semantic distance. The intervention intentionally expanded students' creativity (data-driven visualization, kinetic sculpture, choreographic models), providing exactly the kind of heterogeneous practice that Koutstaal et al. [28] consider to be the driving force behind flexible, original responses. The discrepancy between object and context enhances cognitive originality and flexibility but does not contribute to the expansion of linguistic fluency [29]. Interconnected tasks have typically been designed on the basis of the principle of income matching, aligning scientific schemes with artistic means (e.g., schemes as ecosystems; fractions as textile mosaics). Reducing stereotypicality and incorporating cross-disciplinary metaphors in artifacts aligns with revenue-matching goals, liberating students from cognitive fixation while preserving functional utility through design constraints; much like VR data, where unusual contexts stimulate conceptual exploration.

Dispositional creativity increased modestly, and organizational/communicative tendencies improved with a typical mid-year wobble in Ko. This pattern is consistent with the project-management literature: perceived training value and conducive communication climates fortify connections among social interaction, trusting, and creativity; impacts on adaptability may be weaker or slower to appear [30]. The fidelity gradient and PD model (authentic integration, shared rubrics, shielded planning time) align with system-level syntheses highlighting classroom climate and faculty capability as pivotal levers for durable STEAM implementation [31]. Partial mediation of originality/constructive activity by Kk/Ko implies that social processes (role negotiation, critique talk) are not a contextual backdrop; instead, they mediate design cycles as they yield cognitive benefit.

The findings support structured imagination over unregulated ideation. The Dynamic Framework's hypothesis that unfettered moving thought should strongly covary with divergent thinking was given mixed or no support by recent studies [32]. The cycles of design thinking (empathize–define–ideate–prototype–test) appear to have embodied appropriate constraints: sufficient liberty to generate options and sufficient structure to refine them—a balance also predicted by developmental accounts of imagination as an engine of social cognition [33]. Philosophically and neuro-scientifically, it stands between Tse's [34] thesis of free imagination as the fount of human agency and the practical imperative of school settings' need for guardrails; studio critique and parity-of-assessment serve as such, directing imagination into deflectable artefacts rather than idealizing unfettered ideation.

It is advised in the literature not to assume identical superiority of STEAM compared to STEM in originality [26]. Moderate-to-small gains in originality, compared with moderate-to-large gains in flexibility and constructive activity, align with that pattern. Theories of symbolic competence in education and of studio practice argue for tenable sequencing: as students build semiotic repertoires and learn to restructure forms (constructive activity), they become qualified for originality; only with ample variety of creative activity and intentional incongruency in components of that creative activity [29] do increments of originality accumulate. Dose-response and fidelity gradients, combined with the late increase from T2 to T3, align with such accumulation.

The data from Ukrainian programs show that integrated arts also support nonverbal thinking, school performance, and well-being, alleviating stress and complementing peer interaction even in disruptive environments. Co-participation and motivational benefits (Kk/Ko, GCA) conform to and extend the wider policy case that STEAM must foster socio-emotional skillsets and cultural competence in addition to disciplinary knowledge. In this context, the arts are not an indulgence but a psychologically moderating format through which scientific concepts become graspable and transferable, and civic tendencies can be rehearsed.

The moderation results clarify how Strelau's Regulative Theory of Temperament (RTT) shapes the course of STEAM learning. Students who were higher in nervous process mobility and better balanced in their excitation/inhibition ratio showed larger constructive activity and categorical flexibility gains, as well as fewer refusals. From an RTT perspective, studio-style design cycles need rapid switching from exploration to evaluation; mobility allows for such switching, with balance preventing over-reaction to new experience. These relationships complement moves to link RTT to five-factor models, with mobility and endurance-like traits loading on higher-order plasticity/extraversion, sensation seeking, stability/conscientiousness, and emotionality factors [18,35].

4. Discussion

This study demonstrated that an authentically integrated, art-centered STEAM elective produced reliable, moderate gains in creative cognition, particularly in representational flexibility and constructive activity, with smaller but significant improvements in originality. These effects emerged by mid-year and consolidated by year-end, indicating that iterative design-thinking cycles first reshape exploratory behavior and later yield more original artefacts. Improvements in communicative and organizational skills partially mediated creative outcomes, and temperament traits, including mobility and balance of excitation and inhibition, moderated, but did not determine, these gains.

The findings also contribute to ongoing debates about the psychometric and neurobiological bases of creative flexibility. Traits such as mobility and excitation/inhibition balance appear to align with energetic factors in broader personality models, yet they likely involve distinct neurochemical substrates. Future studies could strengthen inference by combining temperament questionnaires with behavioral indicators of cognitive switching and physiological measures, such as students' dilation during critique or actigraphy during project sprints. These multimodal data would help clarify whether observed flexibility gains stem primarily from neurodynamic responsiveness, environmental structure, or their interaction.

The primary outcomes here operationalize creativity-related competencies (divergent and flexible thinking, visual imagination, and process-proximal artefact features) and a socio-collaborative pathway, rather than direct STEM conceptual understanding or STEM attitudes. This aligns with concerns in the STEAM literature that creativity is frequently invoked but rarely measured, and that arts components are sometimes treated ornamentally rather than as a discipline with its own epistemic standards [6]. The present results are therefore positioned as evidence that a thickly authentic, art-centered STEAM elective can produce measurable creative gains under school-realistic conditions; however, claims about improved STEM achievement should be treated as hypotheses requiring additional data (e.g., unit-aligned STEM concept inventories, attitudinal measures, and/or systematic analysis of STEM reasoning in student artefacts) [36].

The results of the temperament study help explain why the increase in flexibility exceeded the increase in originality [29]. Within Strelau's Regulative Theory of Temperament, mobility supports rapid switching between exploration and evaluation, while balanced excitation and inhibition prevents overreaction to novelty [37]. This pattern is reflected in the data: students higher in mobility and balance achieved greater categorical flexibility and constructive activity, while even those with less optimal profiles benefited when instruction maintained high fidelity and clear design cycles. In short, temperament modulates, but does not limit, the capacity for creative development in well-structured STEAM settings.

This study offers a practical set of classroom activities that enable teachers to experience the benefits of a genuinely integrated STEAM approach, in which the arts drive inquiry rather than serve as mere decoration. The research findings are translated into everyday routines, design tools, and assessment methods suitable for typical schools, including those with limited resources, treating diversity and fundamental inconsistencies as manageable challenges rather than obstacles. Project sequencing that demands students to collaborate in various media and to embed STEM concepts in unlikely artistic settings diminishes fixation and broadens semantic search, where the greatest gains were realized. In practice: alternate two- and three-week sprints that actively change materials (paper → textile → cardboard engineering) and representational modes (diagram → narrative image →

kinetic piece) and accompany each flip with a brief "why this medium?" discussion so students learn to defend representational decisions rather than just tool-switching.

The design thinking cycle of empathy, definition, ideation, prototyping, and testing was operationalized as a weekly instructional routine. Each week commenced with targeted empathy activities on Mondays, including observations, interviews, and field notes. Midweek sessions were allocated to prototyping and structured critique, while Fridays focused on project revisions and brief presentations. Critiques employed standardized sentence stems such as "I noticed… I wonder… Have you considered…" and rotated participant roles, including creator, explainer, questioner, and summarizer, to stabilize discussion dynamics. Mid-semester, occasional fluctuations in the organization of roles were permissible; however, for three consecutive classes, roles were maintained consistently to allow social and procedural norms to consolidate. Evaluation relied on shared criteria that equally addressed the process, including research skills, breadth of ideas, responsiveness to feedback, and rigor of iterative development, as well as the outcomes, including aesthetic coherence, conceptual accuracy, systems thinking, and clarity of diagrams. Portfolios, comprising three artifacts per unit accompanied by documentation of the creative process, and concise exhibitions with a jury, were integral components of assessment. Student work was evaluated separately according to art-specific and STEM-specific criteria, with inter-class moderation conducted twice per semester to ensure reliability. Children's creative outputs were interpreted as cognitive traces, providing insights into their thinking processes rather than serving as decorative objects.

Research should include measures that fit the students' chronotype and temperament, without labeling them. Students with high mobility are expected to generate bursts of ideas, but before developing a prototype, they will need clear guidance on closing the prototype. Students with limited mobility benefit from switchable checklists and visual examples of small but highly effective design options. When timetabling permits, intensive critique and making sessions should be scheduled at chronotype-compatible times, or at least at consistent times of assessment. Quiet construction settings are recommended for students with high reactivity, complemented by timed gallery walks to regulate social load. Professional development should focus on three skills identified as critical both by teacher reports and fidelity data: writing co-equal learning goals between art and STEM, conducting ten-minute micro-critiques to reduce fixation and regularize revision, and co-grading with parity. Weekly cross-discipline co-planning sessions of approximately thirty minutes are advised, using a two-page observation checklist to document aims, explicit art and STEM connections, evident design cycle phase, and parity dialogue during peer walk-throughs. The utility of professional development should be treated as a design requirement, with each session producing a directly applicable routine or rubric.

Materials that afford movement and manipulation, such as paper, offcuts, packaging, gaffer tape, string, binder clips, and sellotape, should be prioritized. Small DC motors and LEDs can be included when available, with mechanical substitutes, including cams, pulleys, and stop-frame alternatives, used in low-budget contexts. Students' phones can be used to document iterations while maintaining analogue work to lower participation barriers. Public sharing of work can be facilitated through corridor pop-up galleries following critique. Integrated lessons must ensure that both an art component, including composition, motif, dramaturgy, or material transformation, and a STEM component, including measurement, modeling, or constraint satisfaction, are explicitly present. Lessons failing to meet this criterion are considered unintegrated. Assessment practices should remain vigilant against reversion to product-only grading, with mid-unit checks emphasizing journals and iterative evidence. In cases where originality lags behind flexibility, scaffolding should avoid prescriptive tricks of novelty, maintaining high task variety and specific critique. Analytical models incorporating a teacher random effect produced near-identical Group × Time estimates to two-level specifications, suggesting limited teacher-driven confounding (Table 6).

Table 6. From result to routine: a quick mapping for teachers.

Design lever	Concrete classroom moves	What it provides (based on the findings)	What to watch
Varied creative experiences across media	Rotate media/modes every 2–3 weeks; requires a "translation" of the same STEM idea into two forms	Bigger gains in categorical flexibility and reduced stereotypy	Do not let "translation" become superficial; demand a short rationale
Principled incongruency	Pair STEM content with "unexpected" artistic contexts (e.g., circuitry ↔ textile pattern)	More original combinations without losing usefulness	Keep constraints explicit so work stays accurate
Micro-crit protocol (10 minutes)	2 makers present WIP; peers use stems; maker states one revision they will attempt	Early movement in constructive activity; fewer refusals	Enforce brevity; crit is a lever, not a seminar
Parity rubrics	Two columns (ART/STEM), equal weight; co-grade	Aligns with assessment parity theory; stabilizes expectations	Moderate marks twice a term to avoid drift
Role rotation in teams	Fixed roles for 3 sessions; then rotate	Improves Kk/Ko over time; smoother mid-term	Expect a T2 dip; persist through the wobble
Temperament-aware switching aids	Visual timers, "next-action" cards, exemplars of micro-changes	Helps low-mobility students enter iteration; reduces avoidance	Avoid pigeonholing students by trait labels
Chronotype consistency	Keep assessment windows steady; place crit/making when alertness is higher	Reduces noise in attention-dependent tasks	If timing must vary, document it

Source: created by the authors

Curriculum sequence, lesson routines, and illustrative student artefacts are described in the Materials and Methods section (intervention curriculum and learning activities). The discussion below focuses on interpreting outcomes and implications. In the first 2 weeks, the course focused on Geometry and Pattern as Meaning. Students engaged in circle, triangle, and square warm-up exercises, participated in short composition mini-lessons, and completed an initial micro-critique. During weeks 3–4, under the theme Translate and Test, students were tasked with transforming a measurement-based idea into two different media and composing a brief written artist-scientist statement. In weeks 5–6, devoted to Data as Narrative, students collected a small dataset and created an infographic accompanied by a narrative panel. This stage concluded with a critique emphasizing clarity and accuracy.

Weeks 7–8 addressed Motion and Mechanism. Students were introduced to paper mechanisms and simple cams, developed storyboards for kinetic ideas, and engaged in iterative testing and revision. In weeks 9–10, the theme Systems Across Scales guided students to construct layered micro-macro maps, integrate legends and directional arrows, and participate in peer reviews focused on systems thinking. During weeks 11–12, the module Public Share and Reflect culminated in a pop-up gallery featuring juried feedback, a portfolio review based on a parity rubric, and short metacognitive reflections linking creative choices to learning goals. By mid-term, more diverse drawing, bolder mid-construction critiques, and critique discussions shifted from "I like it" to specific suggestions. By end-term, more understandable diagrams, less usual motifs, and students who can articulate why a particular medium best communicates a particular idea. Monitor it with two artefact reviews per term (5–7 minutes each), noting flexibility, constructive modifying, and diagrammatic clarity. To increase your creativity, use a variety of methods, not just creative techniques.

This was a clustered quasi-experiment with voluntary uptake, so residual selection cannot completely be ruled out, although baseline balance and random-effects modeling were used. Scalar invariance of measurement was partial for KOS; corrections were applied using aligned means, but caution remains when comparing mean values between groups. Scoring of originality, by virtue of experimental design, is cohort-relative; it would help portability to import semantic-distance measures. Incongruency and variety were not varied in the design; future trials could factorially manipulate these design tenets, incorporate measures of chronotype, and include behavioral or physiological indicators of cognitive control to refine mechanistic inference.

The quasi-experimental allocation by timetabling, though pragmatic, begrudges causal interpretation despite acceptable overlap over baselines and strong clustered modeling. Heterogeneity from teacher assignment was a plausible source, but fidelity models with teacher random effects produced nearly the same result. Coaching by fidelity took place between cycles of observation as an implementation support; although probably valuable, this is part of the program package in the real-world setting and will probably restrict isolation of pure content effects. Data systems under emergency contexts prevented the inclusion of standardized prior attainment for all students. This was addressed through multivariate baselines and sensitivity analyses.

It is necessary to introduce diversity and fundamental discontinuity into the sequence of projects in order to promote flexibility and novelty. A commitment to professional development for teachers with practical value improves the atmosphere of classroom discussions, which in turn promotes creative activity. For research, include computational novelty measures, chronotype covariates, and multimodal indicators of switching to mediate among temperament mechanisms. The results justify the mechanism hypothesis: the A in STEAM, duly enabled, retools students' thinking with symbols, collaboration with others, and transporting of ideas from doodle to presentable, exercisable artefacts. Adaptability precedes creativity, provided that design iterations continue to flow, contexts remain fruitfully mismatched, and creative activities are highly diverse.

5. Conclusions

This research provides supporting evidence that an authentically integrated, art-centered STEAM approach, enacted with design-thinking cycles and assessment parity, realizes consistent gains in students' creative cognition on art-proximal, performance-based measures. During the course of a school year, the intervention produced moderate gains in representational diversity, reflected in higher imagination, greater plot flexibility, and reduced stereotypy, as well as in constructive sophistication, measured by categorical flexibility and constructive activity. Smaller but significant increases were observed in rarity-weighted originality, along with fewer avoidance responses. Process-proximal indicators improved first (by T2), followed by consolidation of product-level results by T3, consistent with the theorized sequence from iterative practice to artefactual innovation.

Social-cooperative abilities were enhanced in parallel with creative productivity. Knowledge organization system (KOS) increases partially mediated originality and constructive behavior gains, such that critique talk, role negotiation, and time-boxing, far from being backdrop conditions, operate as vehicles whereby studio procedures gain cognitive advantages. Effects were scaled with implementation fidelity and instructional dose, highlighting that co-planning, overt arts–STEM connections, and assessment parity are key levers of influence rather than niceties. According to Strelau's Regulative Theory of Temperament (RTT), students with higher mobility and balanced excitation/inhibition achieved greater success with fewer failures, while classes that maintained high teaching accuracy compensated for less optimal neurodynamic profiles. This is an argument for a pragmatic stance: well-supported scaffolding of design cycles can broaden access to flexible thinking regardless of differences in baseline switching or reactivity profile. The study demonstrates the value of children's artworks as cognitive traces data comparable to scientific representations in a longitudinal, clustered design in a high-disruption, resource-constrained environment.

Within the Ukrainian context, the results reinforce neuropedagogical imperatives recorded in the midst of long stress and interference: STEAM-integrated activities present balancing routines, embodied symbolism, and mastery-as-cooperation activities that assist in apportioning cognitive load and promoting persistence in STEM learning. Limitations are the quasi-experimental design with voluntary uptake, partial scalar invariance of one social measure, and limited control of chronotype; originality measures were cohort-normative. Despite that, effects were resilient to checks of sensitivity, and gradients vs. fidelity/dose fortify causal explanation.

Implications for policy and practice are as follows: safeguard teacher co-planning and PD in authentic integration; implement assessment parity (process and product equal weight); and design variety and principled incongruency in and between media and contexts to foster first flexibility and then originality. Future research must randomize or step-wedge at the cluster or region level, manipulatively factor in variety/incongruency, embed chronobiological measures, and include human ratings with computational measures of semantic distance complemented by behavioral/physiological measures of cognitive control in order to fine-tune mechanisms and durability.

Author contributions

Liudmyla S. Brovchak: Conceptualization, Writing – review & editing; Lesia V. Starovoit: Formal analysis, Methodology, Project administration; Iryna B. Shvets: Supervision, Validation, Visualization; Larysa M. Likhitska: Conceptualization, Data curation, Writing – original draft; Liudmyla Vasylevska-Skupa: Resources, Methodology, Funding acquisition, Investigation.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors state that they have no personal relationship that might have inappropriately influenced them in writing the current paper.

Ethics declaration

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Appendix A. Overview of the four-unit STEAM elective: driving questions, practices, constraints, artefacts, and documentation

Unit	Driving question / design brief (student-facing)	Core arts practices (how meaning is made)	Core STEM practices (how constraints are tested)	Key constraints (explicit criteria)	Main artefact (portfolio outcome)	Evidence collected (for transparency & assessment parity)
Unit 1: Representation & Pattern	How can we represent an idea so that it is both expressive and rule-consistent?	Visual symbolism; composition; iterative sketching; visual contrast & balance	Rule-governed transformation; modelling with constraints; basic measurement/ratio checks (where relevant)	Aesthetic: coherence, balance, legibility; STEM-linked: rule compliance, consistency across transformations	Multi-version representation set (2-3 representations + final)	Drafts; transformation rule sheet; critique notes; revision plan; final artefact; brief reflection
Unit 2: Structure & Stability	How can we design a structure that is stable, efficient, and aesthetically coherent?	Material exploration; spatial composition; form-function integration; critique & refinement	Structural reasoning; testing stability; measurement (dimensions, symmetry/centre); constraint satisfaction	Aesthetic: harmony, proportionality, purposeful form; STEM-linked: stability under test, dimensional constraints, material limits	Constructed model/prototype + annotated diagram	Sketches; prototype photos; test record (pass/fail + notes); critique sheet; revision plan; final model; reflection

Unit 3: Mechanism, Movement & Iteration	How can a designed object produce a predictable effect or movement while communicating an idea?	Narrative/meaning through form; sequencing; design aesthetics; revision based on feedback	Mechanism logic; cause-effect modelling; iterative testing; calibration via measurement/marking	Aesthetic: clarity of intent, design unity; STEM-linked: reproducibility of effect, accuracy to constraints, iterative improvement	Functional artefact (mechanism /interaction) + process storyboard	Storyboard; drafts; prototype iterations; test log; critique notes; final artefact; short reflection
Unit 4: System, Data & Exhibition	How can we communicate a system (environmental/social/technical) through an artefact that is accurate and compelling?	Visual storytelling; multimodal display; curation; peer critique; exhibition standards	Systems thinking; modelling relationships; using data/parameters as constraints; justification of design choices	Aesthetic: communicative power, coherence, audience readability; STEM-linked: internal consistency, parameter alignment, evidence-based justification	Exhibition-ready artefact + poster/label explaining constraints and choices	Draft poster/label; intermediate versions; critique notes; final artefact; final label/poster; reflection

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