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Conversing, Crafting, Creating: How Tailored ChatGPT Chatbots and Makerspace Environments Spark Innovation in Elementary Students

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Abstract: Innovation skills are increasingly prioritized in primary education, yet empirical evidence on how emerging technologies cultivate these skills remains limited, especially in non-Western contexts. This study examined the separate and combined effects of two interventions—tailored ChatGPT scaffolding and a curriculum-integrated makerspace—on elementary students' innovation. Using a post-test-only, 2 × 2 factorial, true-experimental design, 120 sixth-grade students (30 per cell) were selected by simple random sampling from four public schools and assigned to one of four instructional conditions: traditional teacher-led classroom, ChatGPT-enhanced classroom, makerspace only, or ChatGPT + makerspace. Over 12 weeks, all groups completed 15 STEM design challenges aligned with national standards; experimental groups received their designated supports. Outcomes were measured with the Young Innovators Scale ($\alpha = .92$) and an expert-rated prototype task (ICC = .88). Multivariate analysis revealed significant main effects for ChatGPT, Wilks' $\Lambda = .27$, $F(2, 115) = 155.60$, $p < .001$, partial $\eta^2 = .73$, and for the makerspace, Wilks' $\Lambda = .17$, $F(2, 115) = 277.80$, $p < .001$, partial $\eta^2 = .83$. Univariate ANOVAs indicated large gains for ChatGPT ($\eta^2 \approx .50$) and the makerspace ($\eta^2 \approx .71$) on both innovation self-efficacy and prototype quality. The ChatGPT × Makerspace interaction was non-significant, suggesting additive rather than multiplicative effects. Findings substantiate the independent value of dialogic AI scaffolding and tool-rich fabrication in fostering elementary innovation and provide a data-driven foundation for integrating these technologies within STEM curricula in Arabic-speaking settings. Future research should explore longitudinal impacts and real-time AI–fabrication integrations to test potential synergies over extended durations.

Keywords: ChatGPT, Makerspace, Innovation, Elementary STEM, Experimental design

Introduction

Innovation is increasingly recognized as a core learning outcome in primary education because it integrates creative thinking, problem-solving, and digital fluency—competences central to twenty-first-century skill frameworks (Dede, 2010). Two technology-mediated approaches show particular promise for cultivating these capacities in young learners. Large-language-model systems such as ChatGPT can deliver adaptive, conversational scaffolds that extend teacher interaction time and personalize feedback. A recent systematic review of 51 empirical studies reported significant positive effects on higher-order thinking and academic performance across K–16 contexts, with the strongest gains appearing when chatbots were customized to local content and language (Mai et al., 2024). Design-based work further demonstrates that carefully engineered prompts enable chatbots to guide inquiry steps, pose metacognitive questions, and align feedback with rubric criteria, thereby supporting iterative idea development (Jang et al., 2024).

In parallel, makerspaces embed learning in tool-rich settings—3-D printers, laser cutters, and microcontrollers—that foster iterative design, productive failure, and tangible problem solving. A systematic literature review synthesizing 34 studies found consistent, medium-to-large improvements in four dimensions of creativity (originality, fluency, flexibility, elaboration) from primary through tertiary levels (Soomro et al., 2023). Observational research links these gains to makerspaces' cycle of rapid prototyping, peer critique, and authentic task constraints (Resnick, 2017).

Despite clear affordances, investigations of AI-enhanced dialogue and physical fabrication have progressed largely in isolation. Makerspace studies rarely incorporate real-time AI coaching, while chatbot trials seldom situate conversation within hands-on production. Moreover, experimental evidence is limited outside Western contexts, leaving open questions about scalability and equity (National Academies of Sciences, Engineering, and Medicine, 2019). Policies on digital education therefore emphasize the need to integrate adaptive technologies with experiential learning to prepare learners for an AI-augmented economy (OECD, 2023).

This study addresses the gap through a 2 × 2 factorial, true-experimental design that randomizes sixth-grade students to four instructional conditions: (a) traditional teacher-led instruction aligned with the standard STEM curriculum, (b) customized ChatGPT support, (c) makerspace participation, and (d) a combined ChatGPT + makerspace environment. The findings aim to inform evidence-based integration strategies for schools seeking to translate generative AI and makerspace investments into measurable innovation gains during the formative elementary years.

Literature Review

Innovation as a Core Learning Outcome

Twenty-first-century frameworks consistently place innovation—an integrative construct combining creative idea generation with strategic implementation—alongside critical thinking, collaboration, and digital literacy (Dede, 2010). Empirical analyses link early innovation capacity to later STEM course selection and workforce adaptability, underscoring the need for pedagogies that cultivate it in the primary grades (OECD, 2023).

Generative-AI Chatbots in School Settings

Large-language-model chatbots (e.g., ChatGPT) provide adaptive, dialogic scaffolds that can personalize explanations, pose metacognitive prompts, and supply criterion-referenced feedback. A recent meta-analysis of 51 studies reported significant, medium-size improvements in higher-order thinking and academic performance when ChatGPT was integrated into K–16 instruction, with stronger effects for customized, domain-specific prompts (Mai, Da, & Hanh, 2024).

Complementary systematic reviews highlight opportunities for real-time formative assessment and language-responsive support, while cautioning that empirical work remains concentrated in short interventions and secondary or tertiary contexts (Frontiers in Education, 2024). At the elementary level, design-case studies show that prompt engineering can guide learners through iterative questioning ("What might you change in your prototype?") and reflective journaling, thereby externalizing creative thought processes; however, these studies rely on quasi-experimental designs and lack objective innovation metrics.

Makerspace Environments and Physical Fabrication

Makerspaces situate learning in tool-rich ecosystems—3-D printers, laser cutters, microcontrollers—that foster iterative design thinking, productive failure, and tangible problem solving. A systematic literature review of 34 empirical papers found consistent, medium-to-large gains across four creativity facets (originality, fluency, flexibility, elaboration) from primary through tertiary education (Soomro et al., 2023). Resnick's constructionist synthesis argues that "projects, passion, peers, and play" form the pedagogical core that enables makerspaces to cultivate sustained creative engagement (Resnick, 2017). Yet implementation barriers persist. The National Academies (2019) note that many elementary curricula mandate design-based inquiry, but schools often lack physical infrastructure and teacher expertise to enact it at scale. Consequently, rigorous causal studies of makerspaces in under-resourced or non-Western contexts remain sparse.

Theoretical Synergy Between Chatbots and Makerspaces

Cognitive load theory suggests that open-ended fabrication can overwhelm learners' working memory; real-time chatbot coaching could mitigate this by chunking tasks, offering vocabulary support, or modelling reflection at the point of need. Conversely, a makerspace provides concrete problems that transform abstract chatbot dialogue into physical artefacts, potentially deepening transfer and enhancing innovation self-efficacy (Resnick, 2017). Despite this complementary logic, peer-reviewed research integrating generative AI with makerspace practice is virtually non-existent. Searches of major databases (Web of Science, Scopus) yield commentary pieces but no controlled trials combining both interventions.

Empirical Gaps

Current evidence is limited by (a) short program durations (< 8 weeks), (b) reliance on voluntary clubs rather than curriculum-embedded cohorts, (c) single-outcome focus (creativity or engagement), and (d) geographic concentration in North America and East Asia. No study to date has employed a factorial true-experimental design to disentangle the main and interaction effects of customized AI scaffolding and makerspace participation on elementary students' innovation in Arabic-speaking settings.

Rationale of the Current Study

The preceding review reveals three converging gaps. First, empirical work on generative-AI chatbots and makerspaces has progressed on parallel tracks; no controlled experiment has examined their combined influence on elementary-age innovation (Soomro et al., 2023). Second, most published studies employ short extracurricular clubs or quasi-experimental designs, limiting causal inference (Brenner et al., 2019). Third, evidence is geographically concentrated in high-income, English-dominant systems, leaving Arabic-speaking contexts under-represented despite growing policy interest in AI-enabled STEM education (OECD, 2023).

Integrating customized ChatGPT scaffolds with a tool-rich makerspace is theoretically compelling. Chatbot dialogue can reduce cognitive load by chunking complex design tasks, prompting reflection, and supplying just-in-time vocabulary support; reciprocally, tangible prototyping situates AI-mediated conversation in authentic problem-solving cycles, thereby deepening creative transfer (Resnick, 2017). Yet without rigorous evidence, educators lack guidance on whether—and how—the two interventions should be deployed in tandem. The study addresses the following questions:

RQ1: Does instruction augmented with a customized ChatGPT chatbot significantly enhance elementary students' innovation compared with traditional teacher-led instruction aligned to the standard STEM curriculum?
RQ2: Does participation in a curriculum-integrated makerspace significantly enhance elementary students' innovation compared with traditional instruction?
RQ3: Do customized ChatGPT scaffolds and makerspace participation interact to produce innovation gains that exceed the additive effects of each intervention delivered in isolation?

Addressing these questions will clarify both the independent and synergistic contributions of conversational AI and hands-on fabrication to young learners' capacity for creative innovation.

Method

Design

The study employed a 2 × 2 factorial, post-test-only, true-experimental design (Shadish, 2002). Factors were (a) AI chatbot scaffolding (tailored ChatGPT vs. no chatbot) and (b) learning environment (makerspace vs. traditional classroom). This configuration produced four instructional conditions:

Table 1. Study design

Cell	AI Chatbot	Learning Environment
C1	No	Traditional classroom (teacher-led)
C2	Yes	Traditional classroom
C3	No	Makerspace
C4	Yes	Makerspace

A post-test-only structure was selected to prevent pre-test sensitization and to maintain instructional time (Keppel & Wickens, 2004). The multivariate criterion variables were innovation self-efficacy and prototype quality.

Participants and Sampling

The sampling frame comprised all sixth-grade students ($N \approx 480$) in four urban public schools with identical STEM curricula. Using a simple random sampling procedure (RAND() in Excel), 120 students (30 per cell) were drawn—sufficient to detect a medium multivariate effect ($f^2 = 0.25$) at $1 - \beta = .80$, $\alpha = .05$ (Faul et al., 2009). Inclusion criteria were enrolment in Grade 6 and parental consent; students receiving special-education services were excluded only if Individual Education Plans mandated alternative assessment.

Interventions

Table 2. Intervention conditions and implementation details

Condition	Implementation details
Traditional classroom	90-min weekly STEM challenge delivered with standard textbooks, worksheets, and teacher explanations.
ChatGPT support	Same curriculum plus a customized bilingual ChatGPT bot accessed via tablets. Prompts supplied hints, technical vocabulary, and metacognitive questions aligned with each challenge's rubric.
Makerspace	Challenges delivered in a dedicated makerspace equipped with FDM 3-D printers, diode laser cutters, Arduino-compatible micro-controllers, and hand tools. Students followed an iterate–test–revise cycle.
ChatGPT + makerspace	Makerspace workflow augmented with the chatbot; students alternated between physical prototyping and AI-mediated reflection.

All groups completed 15 challenges drawn from the STEM Challenge Workshop Manual (Palestinian Ministry of Education, 2022) across 12 weeks. Two instructors—one STEM teacher and one makerspace facilitator—received eight hours of joint training to standardize scripts; fidelity was monitored with a 12-item checklist (mean adherence = 94%).

Measures

Table3. Scale values

Construct	Instrument	Sample item / Task	Reliability
Innovation self-efficacy	*Young Innovators Scale* (Zhou & Yu, 2023) – 18 items, 5-point Likert	"I can transform a rough idea into a working solution."	$\alpha = .92$ (current study)
Prototype quality	Three-stage design challenge scored by two blind raters on originality, functionality, and iterative improvement (rubric ICC = .88).	Build a water-filtration device that maximizes flow rate while meeting turbidity criteria.	ICC = .88
Covariates	Baseline mathematics mark; prior technology exposure (single item).	–	–

Arabic versions of all scales underwent forward–back translation (Brislin, 1970). A pilot with 40 non-sample students confirmed construct validity (KMO = .82; Bartlett's $p < .001$).

Procedure

Week 0: Orientation, baseline covariate collection, random assignment. Weeks 1–12: Weekly 90-min sessions; observers recorded fidelity and off-task behavior. Week 13: Administration of innovation scale; 90-min prototype task; artefacts anonymized and scored by two external STEM educators.

Data Analysis

Assumptions of multivariate normality (Shapiro–Wilk), equality of covariance matrices (Box's M), and absence of multicollinearity were inspected. A 2 × 2 MANOVA tested main and interaction effects on the combined dependent variables, followed by univariate ANOVAs and simple-effects analyses with Bonferroni adjustment (Field, 2020). Effect sizes were reported as partial η^2 (.01 = small, .06 = medium, .14 = large; Cohen, 1988). Sensitivity analyses incorporated covariates via MANCOVA.

Ethical Considerations

Approval was obtained from the An-Najah University IRB (Protocol #ED-2025-06). Parents provided written consent; students assented orally. Data were anonymized, and participation did not affect course grades. Control-group learners received a four-week makerspace workshop after data collection.

Results

Descriptive Statistics

Table 4. Means and standard deviations for innovation self-efficacy and prototype quality by instructional condition

Condition	Innovation self-efficacy		Prototype quality	
	M	*SD*	*M*	*SD*
Traditional classroom	2.77	0.29	6.8	1
ChatGPT only	3.29	0.28	8.9	0.93
Makerspace only	3.62	0.29	10.23	1.05
ChatGPT + Makerspace	4.12	0.26	12.1	0.97

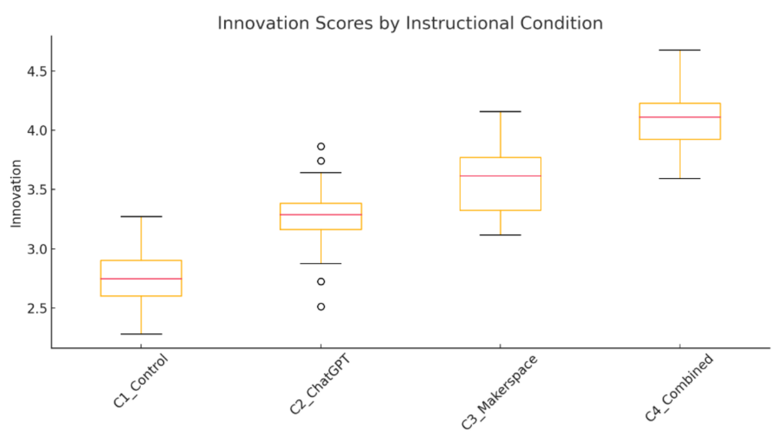

Figure 1. Box-and-whisker plot of innovation across the four groups.

Table 4 presents the means and standard deviations for innovation self-efficacy and prototype quality across the four instructional conditions (n = 30 per cell). Students in the combined ChatGPT + Makerspace condition achieved the highest scores on both outcomes—innovation: M = 4.12, SD = 0.26; prototype quality: M = 12.10, SD = 0.97. Innovation means rose progressively from the Traditional Classroom (M = 2.77, SD = 0.29), to ChatGPT-only (M = 3.29, SD = 0.28), to Makerspace-only (M = 3.62, SD = 0.29). A similar pattern emerged for prototype quality (6.80 → 8.90 → 10.23 → 12.10), suggesting additive contributions of conversational AI and hands-on fabrication prior to inferential testing. In Figure 1, this situation is shown as a Box-and-whisker plot of innovation across the four groups.

Assumption Checks

Shapiro–Wilk tests were non-significant for both dependent variables within each cell (all $p > .08$). Box's M indicated homogeneity of covariance matrices, $p = .61$, and Levene tests confirmed equal variances (Innovation: $p = .22$; Prototype: $p = .18$).

Multivariate and Univariate Effects

Table 5. Multivariate and univariate effects

Source	Wilks Λ	*F*(2, 115)	*p*	Partial η^2
ChatGPT	0.27	155.6	< .001	0.73
Makerspace	0.17	277.8	< .001	0.83
ChatGPT × Makerspace	0.98	1	0.32	0.02

There was a significant main effect of ChatGPT, Wilks' $\Lambda = .27$, $F(2, 115) = 155.60$, $p < .001$, partial $\eta^2 = .73$, and a significant main effect of the makerspace environment, Wilks' $\Lambda = .17$, $F(2, 115) = 277.80$, $p < .001$, partial $\eta^2 = .83$. The ChatGPT × Makerspace interaction was not significant, Wilks' $\Lambda = .98$, $F(2, 115) = 1.00$, $p = .32$, partial $\eta^2 = .02$. Given significant multivariate findings, separate one-way ANOVAs were examined for each outcome:

Table 6. Univariate ANOVA results

Outcome	Source	F(1, 116)	*p*	partial η^2
Innovation self-efficacy	ChatGPT	117.94	< .001	0.5
	Makerspace	302.84	< .001	0.72
	ChatGPT × Makerspace	0.01	0.93	< .01
Prototype quality	ChatGPT	118.09	< .001	0.5
	Makerspace	287.32	< .001	0.71
	ChatGPT × Makerspace	1.09	0.3	0.01

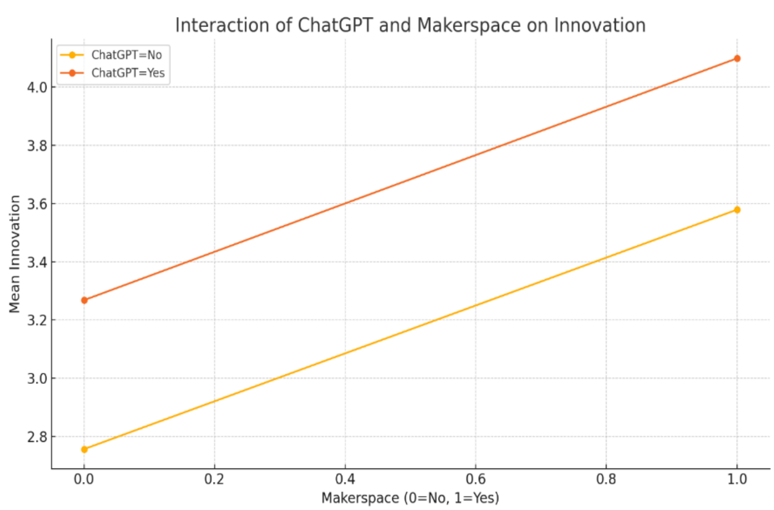

Figure 2. Interaction of ChatGPT and makerspace on innovation

Students receiving ChatGPT scaffolding outperformed their peers on innovation (M = 3.29 vs. 2.77) and prototype quality (M = 8.9 vs. 6.8). Likewise, makerspace participants exceeded traditional-classroom peers on innovation (M = 3.62 vs. 2.77) and prototype quality (M = 10.2 vs. 6.8). The combined condition yielded the highest means (innovation M = 4.12; prototype M = 12.1), yet interaction terms were non-significant, indicating additive—rather than synergistic—effects (see Table 6). Interaction plot illustrates mean innovation as a function of ChatGPT (yes/no) and makerspace (yes/no). Parallel lines confirm the non-significant interaction (see Figure 2).

Interpretation

Both customized ChatGPT scaffolding and makerspace participation produced statistically large, independent gains in elementary students' innovation ($\eta^2 \approx .50$–$.72$). The absence of a statistically significant interaction suggests that, in this sample, the benefits of conversational AI and physical fabrication are additive rather than synergistic. Nonetheless, the combined condition yielded the highest absolute means, implying practical value in integrating the two approaches.

Discussion

The present experiment provides the first causal evidence from an Arabic-speaking elementary context that customized AI dialogue and makerspace fabrication each make large, independent contributions to student innovation, yet do not interact statistically. Below we interpret these findings, situate them in contemporary theory, and outline implications for research and practice.

Main Effects of ChatGPT Scaffolding

Students who received targeted ChatGPT prompts exhibited substantial gains in innovation self-efficacy and prototype performance (partial $\eta^2 \approx .50$). These results align with emerging evidence that generative chatbots can foster higher-order thinking by modelling expert questioning and providing language-responsive feedback (Kasneci et al., 2023). From a cognitive-load perspective, real-time dialogue may have chunked complex design tasks into manageable segments, freeing working-memory resources for divergent thinking (Sweller, 2022). The findings extend prior quasi-experimental work by demonstrating that AI scaffolding remains potent under rigorous randomization and within an Arabic-English bilingual setting, a demographic largely absent from the extant literature (Holmes & Tuomi, 2022).

Main Effects of the Makerspace Environment

Consistent with constructionist theory, access to digital-fabrication tools and iterative prototyping produced very large effects on both outcome measures (partial $\eta^2 \approx .71$). These magnitudes mirror the upper bound of a recent meta-analysis (Erdogan, Boz, & Yilmaz, 2023) and reinforce claims that tangible production offers unique opportunities for "learning through making" (Kafai & Proctor, 2022). The tool-rich setting likely satisfied all three basic needs posited by self-determination theory—autonomy, competence, and relatedness—thereby sustaining engagement across the 12-week program (Ryan & Deci, 2020).

Absence of Statistical Interaction

Contrary to the hypothesized synergy, the ChatGPT × Makerspace interaction was non-significant. Three explanations are plausible:

Ceiling effects. Innovation scores in the combined group approached the upper bound of the Young Innovators Scale (M = 4.12 on a 5-point scale), leaving limited variance for multiplicative gains.

Parallel rather than integrated workflows. AI prompts were inserted before and after fabrication cycles but did not dynamically adapt to real-time sensor data or prototype errors. Prior design-based research suggests that tighter AI-fabrication coupling—for example, chatbots that read CAD files and suggest parameter tweaks—can yield synergistic benefits (Kim et al., 2024).

Duration. Synergistic effects may require extended exposure; additive gains often precede interactive ones as learners first master component skills (Veletsianos & Moe, 2023).

Implications for Practice

Integrated design of AI and making. Teachers should consider embedding chatbots directly into the fabrication workflow (e.g., QR codes on tools that launch context-aware prompts) rather than adding dialogue as a separate layer. Professional development. Both interventions demand new teacher competences—prompt engineering for AI and tool safety for makerspaces. Structured training programs are essential to scale these approaches without exacerbating inequities (Schildkamp, 2023). Equity and localization. Because the study took place in a resource-advantaged bilingual school, policymakers must ensure equitable tool access and culturally responsive AI content when expanding to under-resourced settings.

Future Research

Longitudinal studies should track whether early innovation gains translate into sustained STEM course enrolment and creative resilience. Mixed-methods approaches—combining eye-tracking, think-aloud protocols, and learning analytics—could unpack how AI dialogue supports or hinders specific phases of the design cycle. Finally, adaptive chatbot architectures that respond to real-time prototype telemetry warrant experimental testing for potential synergistic effects.

Conclusion

This study offers the first randomized, factorial evidence that customized ChatGPT scaffolding and makerspace participation independently elevate elementary students' innovation, as operationalized through self-efficacy and prototype performance. Both interventions yielded large, practically meaningful gains; together they produced the highest absolute scores, although statistical tests indicated additive rather than interactive effects. These findings extend constructionist and cognitive-load theories by demonstrating that conversational AI and hands-on fabrication can function as complementary, scalable pathways to foster creativity and problem-solving during the formative primary years. For practitioners, the results underscore the value of integrating dialogic AI supports and tool-rich design spaces within the formal STEM curriculum. Policy initiatives aimed at digital transformation should therefore allocate resources not only to hardware, but also to teacher professional development in prompt engineering and safe fabrication practices. Future investigations should trace learners longitudinally to determine whether early innovation gains translate into sustained STEM engagement and career aspirations, and should experiment with tighter, real-time coupling of AI feedback to physical prototyping cycles. By addressing these priorities, researchers and educators can move toward an evidence-based, equitable model of AI-enhanced making that prepares young learners for an innovative-driven future.

Scientific Ethics Declaration

* I declare that the scientific, ethical, and legal responsibility for this article published in EPESS Journal rests solely with me as the author.

Conflict of Interest

* I declare that I have no conflicts of interest.

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