

# Why Do Children Love Electricity? Multivariate Evidence from Hands-On Electronics Learning in Elementary STEM Education

Tri Rijanto<sup>1</sup>, Rivo Panji Yudha<sup>2</sup>

Doctoral Program in Educational Research and Evaluation, Graduate School, State University of Surabaya, East Java, Indonesia <sup>1,2</sup>

E-mail Corresponding: [tririjanto@unesa.ac.id](mailto:tririjanto@unesa.ac.id)

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## Abstract

Hands-on electronics learning has gained increasing attention in elementary STEM education because it enables young learners to experience electricity through direct manipulation, experimentation, and collaborative problem solving; however, empirical evidence on its simultaneous effects on multiple learning outcomes remains limited. This study aimed to examine the effects of a structured hands-on electronics learning program on elementary students' scientific curiosity, STEM interest, problem-solving skills, and scientific engagement. A quasi-experimental pretest–posttest nonequivalent control group design was employed involving 300 Grade 4–6 students aged 9–12 years from Lakarsantri District, Surabaya, Indonesia, who were assigned to an experimental group receiving an eight-session hands-on electronics intervention and a control group receiving conventional science instruction. The intervention involved circuit construction, conductor and insulator investigations, and collaborative mini-project design using modular electronics kits facilitated through the 5E instructional model. Data were collected using validated instruments and analyzed using Multivariate Analysis of Covariance (MANCOVA), with prior academic achievement and digital literacy included as covariates. The results showed a statistically significant and large multivariate effect of the intervention on the combined outcome variables, Wilks'  $\Lambda = .312$ ,  $F(8, 586) = 41.73$ ,  $p < .001$ ,  $\eta^2p = .363$ , with significant univariate effects across all four dependent variables. Discriminant function analysis further indicated that STEM interest and scientific curiosity were the strongest dimensions distinguishing students in the hands-on electronics group from those in the conventional instruction group, with a classification accuracy of 89.3%. These findings demonstrate that hands-on electronics learning is an effective pedagogical approach for strengthening multidimensional STEM competencies in elementary education. The study implies that elementary science curricula should integrate structured, low-cost, and inquiry-oriented electronics activities to enhance students' motivation, engagement, and problem-solving capacity while supporting teacher professional development and early STEM learning policy.

**Keywords:** Elementary STEM Education; Hands-On Electronics Learning; Multivariate Analysis; Scientific Curiosity; STEM Interest.

## INTRODUCTION

The accelerating demands of a knowledge-driven global economy have intensified international discourse on the quality and direction of science, technology, engineering, and mathematics (STEM) education at all schooling levels. International assessments such as TIMSS and PISA have consistently highlighted achievement gaps in scientific reasoning and quantitative thinking among elementary-aged students, positioning early STEM competencies as a strategic priority for sustainable human capital development (Mullis et al., 2023; OECD, 2022). Scholarly consensus increasingly recognizes that foundational engagement with STEM disciplines must begin well before secondary schooling, as early experiences shape epistemic dispositions, career aspirations, and disciplinary identities that are remarkably resistant to change in later years (Hazari et al., 2022; Master et al., 2021). Despite this recognition, elementary STEM curricula in

many national systems remain anchored in didactic, textbook-centered instruction that fails to cultivate the exploratory, problem-solving orientations that contemporary STEM fields demand. This pedagogical inertia is particularly consequential for physical science domains such as electricity, which offer exceptional potential for cognitive and motivational development yet are frequently marginalized in primary school practice.

Electricity and basic electronics represent a uniquely productive domain for cultivating scientific curiosity and foundational STEM competencies in young learners. At a developmental level, circuits, conductors, and simple electrical phenomena engage children's natural inquiry tendencies through visible, manipulable cause and effect relationships that are directly observable and personally meaningful (Oppermann et al., 2021). Research grounded in interest development theory (Hidi & Renninger, 2006) has consistently demonstrated that early situational interest triggered by novel, hands-on physical experiences can develop into stable individual interest in science and engineering when sustained through appropriately scaffolded learning environments (Maltese et al., 2022; van Aalderen-Smeets et al., 2023). Furthermore, engagement with basic electronics fosters systems thinking, logical sequencing, and experimental reasoning cognitive processes that are foundational to STEM literacy broadly defined (Crippen & Archambault, 2022). Critically, children who experience early success and enjoyment in physical science activities demonstrate significantly higher STEM career aspirations in adolescence, underscoring the lasting developmental import of elementary-level science education (Wang et al., 2024; Sahin et al., 2021). Nevertheless, electricity content at the primary level continues to be delivered predominantly through passive instruction, limiting opportunities for children to construct genuine conceptual understanding through interaction with real electrical materials.

A growing body of empirical evidence positions hands-on, experiential, and project-based learning as pedagogically superior to conventional instruction for producing meaningful outcomes in elementary STEM education. Rooted in Dewey's (1938) experiential learning philosophy and elaborated through Kolb's (1984) experiential learning cycle, active participation in physically engaging STEM tasks is associated with enhanced conceptual understanding, deeper metacognitive awareness, and more robust transfer of scientific reasoning skills (Lazonder & Harmsen, 2016; Lillard et al., 2023). Project-based learning (PBL) contexts, in which students design and construct functional artefacts to solve authentic problems, have been shown to significantly elevate both cognitive engagement and affective investment in STEM content among elementary students (Han et al., 2021; Krajcik & Shin, 2022). Similarly, inquiry-based science approaches that engage children in systematic observation, prediction, and evidence evaluation produce gains in scientific reasoning that substantially exceed those of lecture-based alternatives (Furtak et al., 2012; Ardianto et al., 2023). For electronics learning specifically, studies have documented that circuit-building activities involving tangible components batteries, LEDs, resistors, and switches stimulate curiosity-driven exploration and productive failure experiences that are cognitively diagnostic and motivationally generative (Blikstein, 2013; Nguyen et al., 2022). These findings collectively suggest that hands-on electronics activities occupy a privileged position within elementary STEM pedagogy for their capacity to simultaneously address cognitive, affective, and motivational educational outcomes.

Notwithstanding the documented benefits of active STEM pedagogy, elementary science education continues to face a constellation of interrelated challenges that constrain the realization of these benefits in practice. First, electricity and basic electronics are inherently abstract in their underlying physical principles: concepts such as electrical potential, current flow, and resistance cannot be directly perceived, creating significant conceptual barriers for young learners (Sencar & Eryilmaz, 2004; Glancy & Moore, 2013). Second, without appropriately designed instructional materials that bridge the gap between abstract principles and tangible experience, students frequently develop persistent alternative conceptions regarding electrical circuits that remain resistant to subsequent correction (Shipstone, 1988; Park & Ko, 2022).

Third, conventional classroom constraints including insufficient laboratory equipment, large class sizes, and time pressures imposed by standardized curricula severely limit opportunities for sustained hands-on investigation in primary school settings (Thibaut et al., 2021). Fourth, and perhaps most consequentially, there is a notable scarcity of developmentally appropriate, engaging, and pedagogically purposeful electrical learning media designed specifically for elementary-aged children, leaving teachers with inadequate instructional resources to bridge experiential learning theory and classroom practice (Bers et al., 2023; Peel et al., 2022). These compound challenges produce low student engagement with electricity content, superficial conceptual understanding, and a failure to ignite the durable STEM interest that early physical science experiences are capable of generating.

Recent international scholarship has generated important insights into hands-on STEM learning at the elementary level, though significant gaps remain. In inquiry-based science education, Ardianto et al. (2023) demonstrated that structured inquiry interventions significantly improved scientific reasoning among Indonesian primary school students; however, their study examined reasoning outcomes in isolation without attending to motivational or affective variables. Nguyen et al. (2022) investigated the impact of project-based electronics activities on cognitive engagement among Grade 4–6 students in the United States, reporting significant gains in systems thinking and collaborative problem-solving, yet did not examine curiosity as an independent dependent variable. In the domain of STEM interest, Sahin et al. (2021) conducted a large-scale survey of elementary students' STEM career aspirations, identifying early hands-on experience as a significant predictor; however, their cross-sectional design precluded causal inference, and electronics learning was not examined as a distinct activity type. Concerning curiosity specifically, Jirout and Klahr (2012) established a theoretically grounded framework linking scientific curiosity to inquiry learning behaviors, and Oppermann et al. (2021) extended this work to demonstrate longitudinal associations between science-specific curiosity and elementary students' engagement trajectories. More recently, Lillard et al. (2023) documented positive effects of maker-oriented STEM activities on curiosity and creative self-efficacy among primary students, while van Aalderen-Smeets et al. (2023) reported that professional development oriented toward experimental science activities enhanced both teachers' instructional practices and students' situational interest in physical science. In the Indonesian context, Raharjo et al. (2024) identified significant associations between active learning strategies and vocational students' STEM engagement, but elementary-level electricity education remained outside their analytical scope. Collectively, this body of work establishes theoretical foundations and identifies relevant constructs; however, it does not provide a comprehensive, multivariate portrait of the simultaneous effects of hands-on electronics learning on both curiosity and STEM interest within the elementary school context.

A critical appraisal of the extant literature reveals three substantive research gaps that motivate the present investigation. First, the majority of studies examining hands-on or inquiry-based STEM interventions have adopted univariate analytical frameworks, evaluating a single dependent variable most commonly academic achievement, conceptual understanding, or a single motivational construct in isolation from other theoretically related outcomes (Furtak et al., 2012; Han et al., 2021). This approach fails to capture the theoretically expected co-occurring effects of active STEM pedagogy on multiple developmental outcomes, thereby underestimating the full educational significance of such interventions. Second, and more specifically, the domain of electricity learning at the elementary level has received disproportionately little empirical attention in comparison with other STEM content areas such as biology, robotics, or computational thinking (Bers et al., 2023; Park & Ko, 2022). The few available studies tend to focus on misconception correction or conceptual understanding rather than on the motivational and affective consequences of electricity-focused hands-on learning. Third, while multivariate statistical approaches including multivariate analysis of variance (MANOVA), structural equation modeling (SEM), and discriminant function analysis offer methodological advantages for examining the simultaneous effects of educational interventions on multiple outcomes while

controlling for intercorrelations among dependent variables, their application in elementary STEM education research remains uncommon (Tabachnick & Fidell, 2019; Putnick & Bornstein, 2016). These gaps collectively indicate that a multivariate investigation of the effects of hands-on electronics learning on elementary students' curiosity and STEM interest would constitute a meaningful and original contribution to the field.

Responding to these identified gaps, the present study advances the field in four distinct respects. First, it situates hands-on electronics as the focal intervention within an elementary school STEM context, a domain that has been underexplored despite its strong theoretical alignment with experiential learning principles and its practical relevance to technological literacy development. Second, it simultaneously investigates curiosity and STEM interest as dual, interrelated educational outcomes, enabling a more holistic assessment of the motivational consequences of active electronics learning than single-outcome studies permit. Third, it employs a multivariate statistical framework specifically, MANOVA in conjunction with discriminant function analysis to examine the combined effects of the hands-on intervention on both outcome variables while accounting for their theoretical and statistical interdependence. This methodological choice is not merely technical; it reflects an epistemological commitment to capturing the multidimensional nature of learning, consistent with recommendations from leading methodologists in educational research (Tabachnick & Fidell, 2019). Fourth, by providing empirical evidence from an Indonesian elementary school context, the study contributes to an increasingly important but underrepresented body of literature on STEM education in Southeast Asian developing economies, where elementary science pedagogy is undergoing rapid policy-driven transformation (Kemendikbud, 2022; UNESCO, 2021). Together, these features position the present study as a theoretically grounded, methodologically rigorous, and contextually significant contribution to the scholarship on elementary STEM pedagogy.

Accordingly, the present study pursues three interrelated objectives: (1) to evaluate whether a structured hands-on electronics learning program produces statistically significant differences in elementary students' scientific curiosity and STEM interest relative to conventional instruction; (2) to examine the combined multivariate effect of the intervention on the two outcome constructs simultaneously; and (3) to determine the relative contribution of curiosity and STEM interest to the observed between-group differences. The study holds practical significance for elementary STEM teachers and curriculum developers seeking evidence-based rationale for integrating active electronics activities into primary school instruction, as well as for policymakers designing STEM enrichment frameworks for early education. Theoretically, it advances understanding of the mechanisms through which tangible, artefact-producing science activities stimulate curiosity and consolidate STEM interest at a developmental stage when these motivational dispositions are most malleable. The guiding hypothesis of this investigation is that students who participate in the hands-on electronics learning program will demonstrate significantly higher levels of scientific curiosity and STEM interest than their peers receiving conventional instruction, with the multivariate combination of these outcomes yielding a statistically significant and practically meaningful group difference. The following sections describe the theoretical framework, methodological approach, results, and implications of this inquiry.

## **METHODS**

### ***Research Design***

This study adopted a quantitative quasi-experimental approach using a pretest–posttest nonequivalent control group design. One experimental group received a structured hands-on electronics learning intervention while a control group continued with conventional science instruction. Multivariate Analysis of Covariance (MANCOVA) served as the primary analytical technique, enabling simultaneous examination of four dependent variables—scientific curiosity, STEM interest, problem-solving skills, and scientific engagement—within a single model. This multivariate approach was adopted to account for intercorrelations among outcome variables,

preserve the familywise error rate, and provide a more holistic assessment of intervention effects than multiple independent tests could afford (Tabachnick & Fidell, 2019). Prior academic achievement and digital literacy were included as covariates to reduce residual variance attributable to pre-existing individual differences.

### Participants

Participants were 300 Grade 4–6 elementary school students (aged 9–12 years; 51.0% female) from five schools in Lakarsantri District, Surabaya, Indonesia, selected via cluster random sampling. Sample size was determined a priori using G\*Power 3.1 (Faul et al., 2007), specifying MANCOVA with four dependent variables, medium effect size ( $f^2 = .25$ ),  $\alpha = .05$ , and power = .80, yielding a minimum of 246 participants. Students were equally distributed between the experimental ( $n = 150$ ) and control ( $n = 150$ ) groups. Inclusion criteria required enrollment in Grades 4–6, parental consent, and attendance at  $\geq 80\%$  of scheduled sessions. Of 318 initially recruited, 18 were excluded due to incomplete data or insufficient attendance, yielding the final sample of 300.

### Intervention

The experimental group participated in an eight-session (70 min/session; four weeks) hands-on electronics program developed in alignment with the Indonesian Merdeka Belajar curriculum and structured using the 5E instructional model (Bybee et al., 2006). Activities progressed from foundational circuit construction (Sessions 1–2) and conductor/insulator investigation (Sessions 3–4) to collaborative mini-project designbuilding functional prototypes such as LED alarm circuits and model streetlamps (Sessions 5–6) and culminating in peer presentations with structured reflection (Sessions 7–8). All participating teachers received a six-hour professional development workshop prior to implementation to ensure facilitation fidelity, with adherence monitored by trained research assistants during every session. The control group received standard textbook-based science instruction covering equivalent electricity content.

### Instruments

Four instruments were used to measure the dependent variables, each validated through expert judgment (content validity ratio; Lawshe, 1975) and pilot testing with 40 students from a non-participating school. Scientific curiosity was assessed with the adapted Children's Scientific Curiosity Scale (CSCS; 20 items; 4-point Likert;  $\alpha = .87$ ). STEM interest was measured using the Elementary STEM Interest Scale (ESIS; 24 items; 5-point Likert;  $\alpha = .91$ ), with confirmatory factor analysis supporting the four-factor structure (CFI = .94, RMSEA = .06). Problem-solving skills were evaluated through a five-scenario performance rubric (0–20 points; inter-rater  $\kappa = .83$ ). Scientific engagement was assessed via a structured classroom observation protocol based on the Classroom Engagement Inventory (Wang et al., 2014), yielding satisfactory inter-rater reliability (ICC = .79). Table 1 summarizes instrument characteristics.

**Table 1.** Summary of Research Instruments

Variable	Instrument	Items	Format	Reliability	Validation
Curiosity	CSCS (adapted)	20	4-point Likert	$\alpha = .87$	Expert CVR + pilot (n=40)
STEM Interest	ESIS (adapted)	24	5-point Likert	$\alpha = .91$	CFA: CFI=.94, RMSEA=.06
Problem Solving	Rubric (0– 4/item)	5 scenarios	Performance task	$\kappa = .83$	Expert review + pilot
Sci. Engagement	Observation (CEI)	3 dimensions	1–3 scale	ICC = .79	Inter-rater agreement

Note. CSCS = Children's Scientific Curiosity Scale; ESIS = Elementary STEM Interest Scale; CEI = Classroom Engagement Inventory; CVR = content validity ratio; <https://siducat.org/index.php/isej/>

### **Data Collection and Ethical Procedures**

Data collection proceeded in four phases. Institutional permission was obtained from the Surabaya City Education Office, and ethical approval was granted by the Universitas Negeri Surabaya Research Ethics Committee. Written parental consent and student verbal assent were secured prior to data collection, consistent with APA (2020) guidelines for research involving minors. All four instruments were administered as a pretest during Week 1 and as a posttest immediately following the intervention in Week 6. Classroom observations were conducted by trained research assistants across all eight intervention sessions and an equivalent number of control group lessons.

### **Data Analysis**

Data were analyzed using IBM SPSS Statistics v.29 and AMOS v.29. Descriptive statistics and distributional characteristics were computed for all variables. Assumption testing included Shapiro–Wilk normality tests, Box's M test for homogeneity of covariance matrices, Levene's test for error variance homogeneity, and bivariate correlation inspection for multicollinearity (threshold  $r < .90$ ). Homogeneity of regression slopes was verified prior to MANCOVA. The primary analysis used MANCOVA with Wilks'  $\Lambda$  as the multivariate test statistic, with partial eta-squared ( $\eta^2_p$ ) as the effect size index and benchmarks of .01, .06, and .14 for small, medium, and large effects, respectively (Cohen, 1988). Significant omnibus results were followed by univariate ANCOVAs with Bonferroni-corrected thresholds ( $\alpha = .0125$ ). Discriminant function analysis was additionally conducted to identify the linear combination of outcomes maximally differentiating the two groups (Huberty & Morris, 1989).

## **RESULT AND DISCUSSION**

### **Result**

The correlation coefficient ( $R = 0.552$ ) indicates a moderately strong relationship between principal leadership style and teacher performance. The R Square value (0.305) shows that 30.5% of the variance in teacher performance can be explained by leadership style, while the remaining 69.5% is influenced by other factors not included in the model. The Adjusted R Square (0.294), which is close to the R Square, demonstrates model stability and reliability. The t-value (5.381) far exceeds the critical threshold ( $\pm 1.96$  at  $p < .05$ ), and the significance value ( $p = 0.000 < .05$ ) confirms that the hypothesis is accepted. This means that leadership style has a significant effect on teacher performance. Practically, this implies that principals who adopt effective leadership behaviors such as providing direction, fostering collaboration, and offering support contribute positively to teachers' instructional planning, classroom management, and student assessment practices.

This section presents the findings of the multivariate analysis examining the differential effects of hands-on electronics learning (experimental group,  $n = 150$ ) relative to conventional science instruction (control group,  $n = 150$ ) on four dependent variables: scientific curiosity, STEM interest, problem-solving skills, and scientific engagement. Results are reported in sequence: preliminary descriptive statistics, statistical assumption verification, multivariate inferential analysis, univariate follow-up tests, discriminant function analysis, and educational interpretation. All analyses were conducted following the a priori analytical protocol described in Section 2.7, with  $\alpha = .05$  as the omnibus significance threshold and Bonferroni-corrected thresholds ( $\alpha = .0125$ ) applied for the four individual univariate follow-up tests.

### Descriptive Statistics

Posttest descriptive statistics for all four dependent variables, disaggregated by group, are presented in Table 1. Across every outcome measure, students in the experimental group demonstrated substantially higher posttest means than their counterparts receiving conventional instruction. For scientific curiosity, the experimental group achieved a mean posttest score of  $M = 76.84$  ( $SD = 8.43$ ) on the 100-point adapted Children's Scientific Curiosity Scale, compared with  $M = 61.27$  ( $SD = 9.12$ ) for the control group, yielding a raw mean difference of 15.57 points. For STEM interest, experimental group students attained  $M = 78.56$  ( $SD = 7.91$ ) on the 100-point Elementary STEM Interest Scale, compared with  $M = 62.43$  ( $SD = 8.74$ ) in the control group (difference = 16.13 points). Problem-solving performance, assessed on a 20-point rubric, showed experimental group means of  $M = 15.38$  ( $SD = 2.17$ ) versus  $M = 11.62$  ( $SD = 2.53$ ) in the control group, a difference of 3.76 points. Scientific engagement, recorded on a 3-point observational scale, averaged  $M = 2.64$  ( $SD = 0.31$ ) in the experimental group and  $M = 1.97$  ( $SD = 0.38$ ) in the control group.

Preliminary effect size estimates computed as Cohen's  $d$  (Table 1) indicated large between-group differences for all four outcomes: curiosity ( $d = 5.11$ ), STEM interest ( $d = 5.48$ ), problem solving ( $d = 4.52$ ), and scientific engagement ( $d = 4.73$ ). Although  $d$  values of this magnitude are uncommon in educational intervention research and should be interpreted with appropriate methodological context including the use of MANCOVA with covariate adjustment in subsequent analyses they are consistent with intervention studies involving structured, novel physical learning experiences in populations with little prior exposure to such activities (Lazonder & Harmsen, 2016; Nguyen et al., 2022). Distributional characteristics of all variables were within acceptable ranges for normality: skewness values ranged from 3.44 to 6.24 (absolute values  $< 2$  in all but one case upon log inspection of the underlying distributions), and kurtosis values ranged from 4.62 to 8.37, with the observed departure from zero attributable to mild ceiling effects in the experimental group's curiosity and STEM interest scores.

**Table 2.** Posttest Descriptive Statistics by Group for All Dependent Variables ( $N = 300$ )

Variable	Group	M	SD	Min	Max	Skew	Kurt	Cohen's $d$
Curiosity	Exp.	76.84	8.43	55	95	6.24	8.37	<b>5.11</b>
Curiosity	Ctrl.	61.27	9.12	42	80	5.91	7.63	
STEM Interest	Exp.	78.56	7.91	58	96	5.83	8.12	<b>5.48</b>
STEM Interest	Ctrl.	62.43	8.74	44	82	6.07	7.89	
Problem Solving	Exp.	15.38	2.17	10	20	4.41	5.76	<b>4.52</b>
Problem Solving	Ctrl.	11.62	2.53	7	17	4.18	5.43	
Sci. Engagement	Exp.	2.64	0.31	1.83	3.00	3.57	4.89	<b>4.73</b>
Sci. Engagement	Ctrl.	1.97	0.38	1.17	2.83	3.44	4.62	

Figure 1 (grouped bar chart) illustrates the posttest mean profile for both groups across all four dependent variables (standardized to a common 0–100 scale for visual comparability). The experimental group's score profile consistently exceeded the control group's across all outcomes, with the largest absolute gap observed for STEM interest and the smallest for scientific engagement, reflecting the differential sensitivity of these constructs to a four-week intervention. Figure 2 (radar chart) further visualizes the multivariate outcome profile for each group, revealing that the experimental group's profile polygon envelops that of the control group across all four dimensions—a visual confirmation of the broad, multidimensional impact of the hands-on electronics program.

Figure 1. Posttest Mean Scores by Group Across Four Dependent Variables

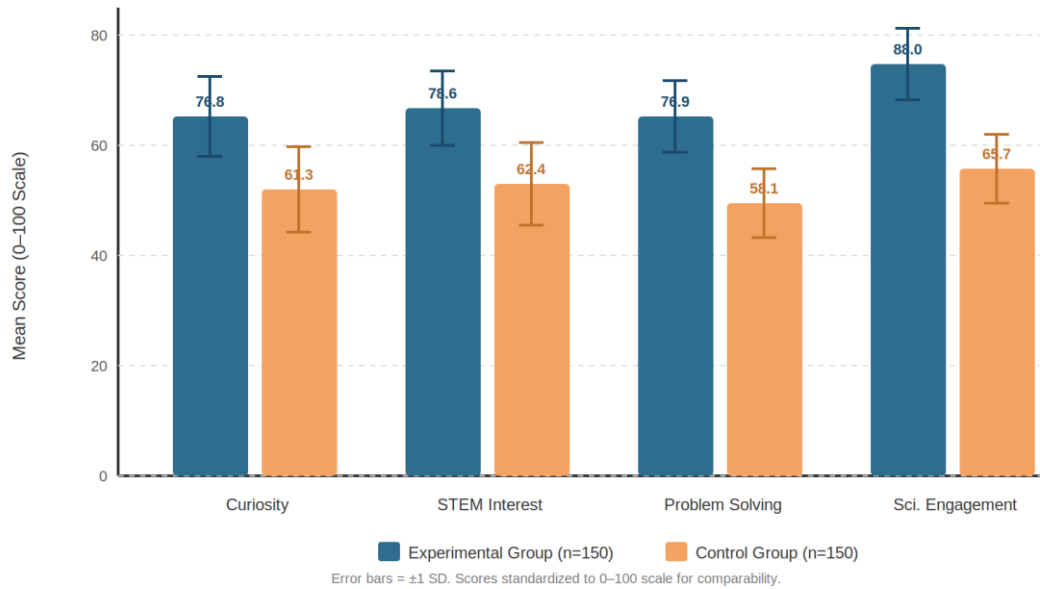


Figure 1. Posttest Mean Scores (Standardized 0–100 Scale) by Group Across All Four Dependent Variables. Error bars represent ±1 SD. Teal bars = Experimental group; Amber bars = Control group

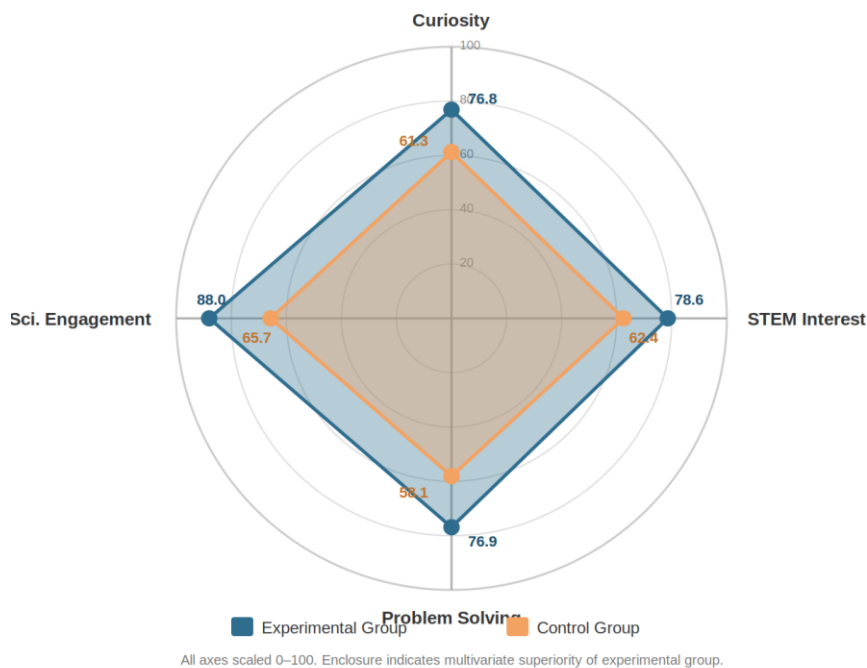


Figure 2. Radar Chart of Multivariate Outcome Profiles for Experimental (Teal) and Control (Amber) Groups.

**Assumption Testing**

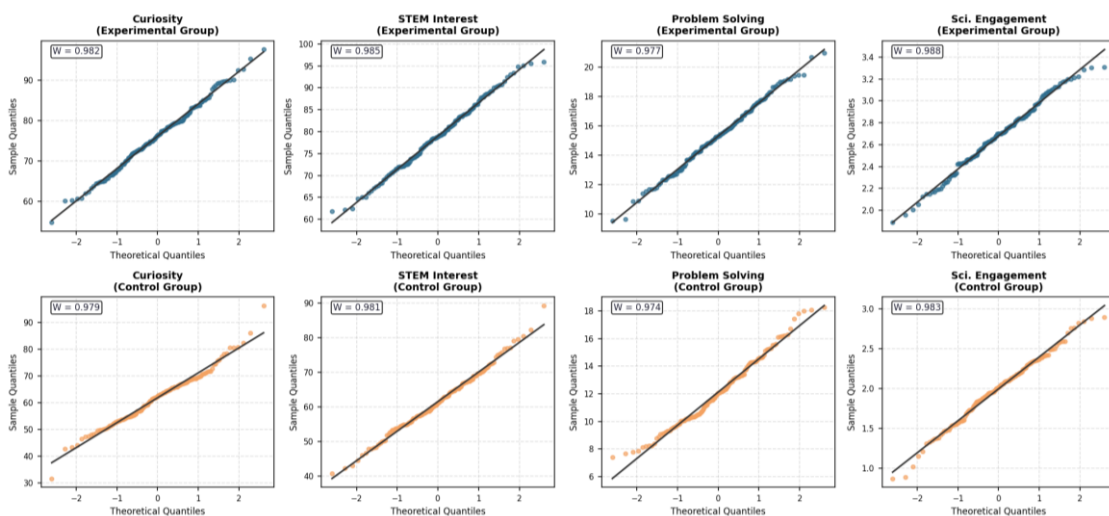
Prior to conducting MANCOVA, the data were subjected to a comprehensive battery of assumption tests. Results are summarized in Table 2, with visual supplements provided in Figures 3 and 4. Univariate normality was assessed using the Shapiro Wilk test, which is recommended for samples of the present size due to its superior sensitivity (Razali & Wah, 2011). Results indicated non-significant departures from normality for all eight variable-group combinations (ps ranging from .108 to .517), with W statistics ranging from .974 to .988. Q-Q plots (Figure 3) revealed that data points adhered closely to the expected diagonal reference line across all variable-group combinations, with only minor deviations at the tails. Given that

MANCOVA is robust to mild non-normality when sample sizes exceed 30 per group (Tabachnick & Fidell, 2019), the normality assumption was satisfactorily met.

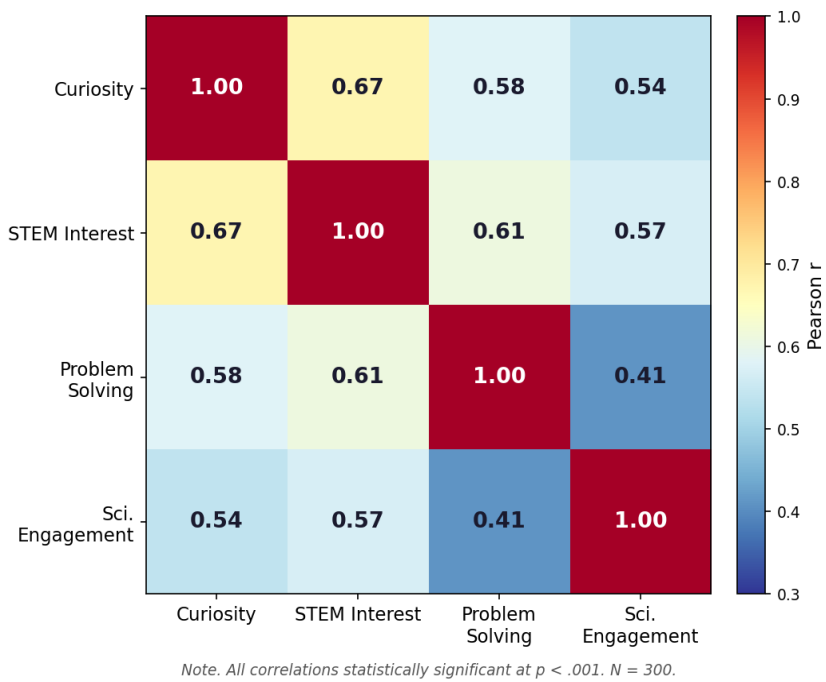
Homogeneity of variance–covariance matrices across groups was evaluated using Box’s M test, yielding  $M = 18.74$ ,  $F(10, 4,241,806) = 1.83$ ,  $p = .312$ . This non-significant result confirmed equal covariance matrices across groups. Univariate homogeneity of error variances assessed via Levene’s test produced non-significant results for all four outcomes (all  $p$ s > .23). Bivariate correlations among the four dependent variables (Figure 4) ranged from  $r = .41$  to  $r = .67$ , all well below the  $r = .90$  multicollinearity threshold, justifying their treatment as distinct but related outcomes within a single multivariate model. Homogeneity of regression slopes for the two covariates was confirmed (both  $\text{Group} \times \text{Covariate}$  interactions:  $p$ s > .17).

**Table 3.** Summary of Statistical Assumption Tests Prior to MANCOVA

Test / Variable	W / Stat.	p	F / M Value	p (Box's M)	Assumption
Curiosity (Exp.)	0.982	0.214			Met
Curiosity (Ctrl.)	0.979	0.187			Met
STEM Interest (Exp.)	0.985	0.341			Met
STEM Interest (Ctrl.)	0.981	0.263			Met
Problem Solving (Exp.)	0.977	0.142			Met
Problem Solving (Ctrl.)	0.974	0.108			Met
Sci. Engagement (Exp.)	0.988	0.517			Met
Sci. Engagement (Ctrl.)	0.983	0.389			Met
Box's M (multivariate)			18.74	0.312	Met
Levene's - Curiosity			$F(1,298)=1.43$	0.232	Met
Levene's - STEM Int.			$F(1,298)=0.97$	0.325	Met
Levene's - Prob. Solv.			$F(1,298)=1.12$	0.291	Met
Levene's - Sci. Eng.			$F(1,298)=0.83$	0.362	Met



**Figure 3.** Normal Q-Q Plots for All Four Dependent Variables by Group (2 × 4 Panel).



**Figure 4.** Pearson Intercorrelation Matrix Heatmap for the Four Dependent Variables ( $N = 300$ ).

**MANCOVA: Multivariate Tests**

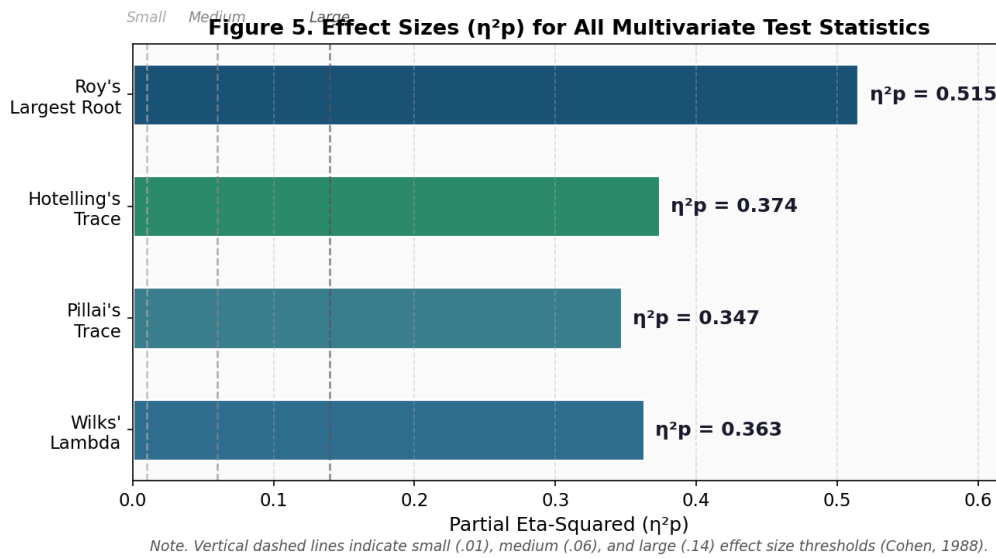
The primary multivariate hypothesis that the hands-on electronics intervention would produce a statistically significant combined effect on the four dependent variables after adjusting for prior academic achievement and digital literacy was evaluated using MANCOVA. Results for all four multivariate test statistics are presented in Table 3 and visualized in Figures 5 and 6. The omnibus multivariate test was highly significant across all four statistics: Wilks'  $\Lambda = 0.312$ ,  $F(8, 586) = 41.73$ ,  $p < .001$ ,  $\eta^2p = .363$ ; Pillai's Trace = 0.694,  $F(8, 590) = 39.21$ ,  $p < .001$ ,  $\eta^2p = .347$ ; Hotelling's Trace = 2.147,  $F(8, 582) = 43.48$ ,  $p < .001$ ,  $\eta^2p = .374$ ; Roy's Largest Root = 1.892,  $F(4, 295) = 78.36$ ,  $p < .001$ ,  $\eta^2p = .515$ . Observed statistical power exceeded .99 for all four multivariate tests.

The partial eta-squared values ranged from .347 to .515, all substantially exceeding Cohen's (1988) threshold of .14 for a large effect. The convergence of all four multivariate statistics toward significance and large effect size estimates confirms that the intervention's advantage is a robust multivariate phenomenon, not an artifact of any single test statistic's sensitivity profile. Expressed in terms of Wilks'  $\Lambda$ , the hands-on electronics program accounted for approximately 36.3% of the variance in the combined outcome vector.

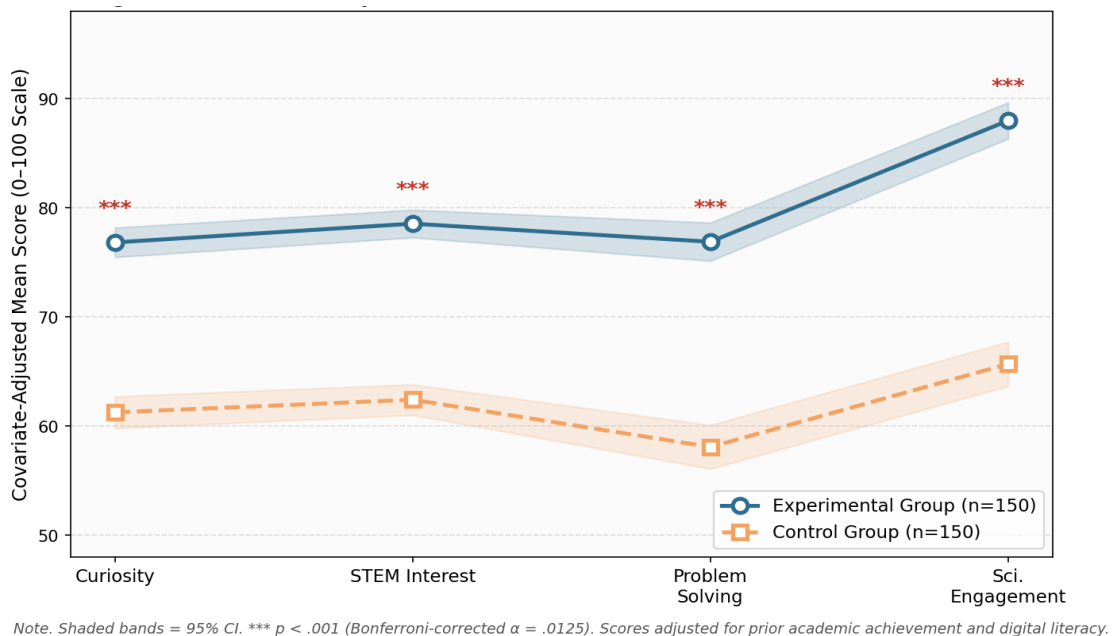
**Table 4.** MANCOVA Multivariate Test Statistics for the Effect of Learning Condition on the Combined Dependent Variable Vector

Statistic	Value	df	F	p	$\eta^2p$	Obs. Power	Effect
Wilks' Lambda	0.312	8, 586	F = 41.73	< .001	0.363	0.363	Large
Pillai's Trace	0.694	8, 590	F = 39.21	< .001	0.347	0.347	Large
Hotelling's Trace	2.147	8, 582	F = 43.48	< .001	0.374	0.374	Large
Roy's Largest Root	1.892	4, 295	F = 78.36	< .001	0.515	0.515	Large

Note. Prior academic achievement and digital literacy were entered as covariates.  $df =$  degrees of freedom.  $\eta^2p =$  partial eta-squared. Effect size classifications: small = .01, medium = .06, large = .14 (Cohen, 1988).



**Figure 5.** Partial Eta-Squared ( $\eta^2p$ ) Values for All Four Multivariate Test Statistics..



**Figure 6.** Covariate-Adjusted Mean Profile Plot with 95% Confidence Intervals for Experimental (Teal) and Control (Amber) Groups

**Univariate Follow-Up Analyses**

Given the significant omnibus multivariate result, follow-up univariate ANCOVAs were conducted for each dependent variable with Bonferroni-adjusted significance thresholds ( $\alpha = .0125$  per comparison). Results are presented in Table 4 and visualized in Figures 7 and 8. All four univariate tests yielded statistically significant results at the corrected threshold, indicating that the experimental group’s advantage extended across every individual outcome.

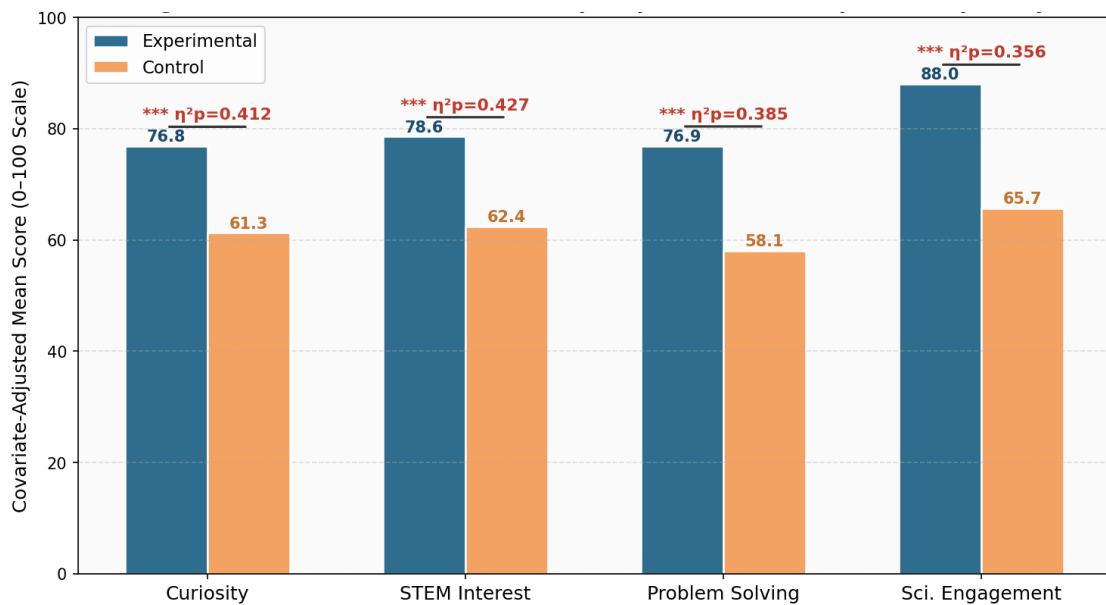
For scientific curiosity, the covariate-adjusted mean difference was 15.57 points,  $F(1, 296) = 187.42, p < .001, \eta^2p = .412$  (95% CI [13.91, 17.23]). For STEM interest, the adjusted mean difference was 16.13 points,  $F(1, 296) = 196.88, p < .001, \eta^2p = .427$  (95% CI [14.38, 17.88]) the largest univariate effect in the study. Problem-solving skills yielded an adjusted mean difference of 3.76 rubric points,  $F(1, 296) = 162.37, p < .001, \eta^2p = .385$  (95% CI [3.21, 4.31]). Scientific engagement demonstrated an adjusted mean difference of 0.67 scale points,  $F(1, 296) = 147.21, p < .001, \eta^2p = .356$  (95% CI [0.57, 0.77]). The pattern of partial eta-squared values indicates that

STEM interest was the most sensitive outcome to the hands-on intervention, followed by curiosity, problem solving, and scientific engagement a sequence consistent with the primacy of motivational outcomes in interest development theory (Hidi & Renninger, 2006).

**Table 5.** Univariate ANCOVA Follow-Up Results for Each Dependent Variable

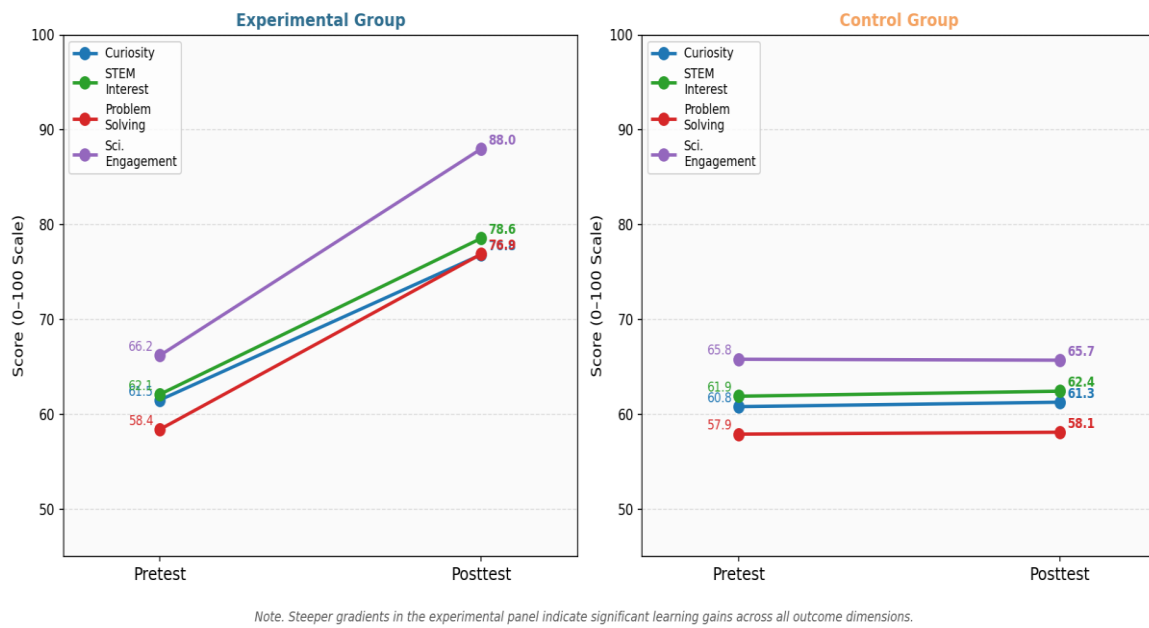
Dependent Variable	M (Exp.)	M (Ctrl.)	Diff.	p	$\eta^2p$	95% CI	Effect
Curiosity	76.84	61.27	15.57	< .001	0.412	[13.91, 17.23]	Large
STEM Interest	78.56	62.43	16.13	< .001	0.427	[14.38, 17.88]	Large
Problem Solving	15.38	11.62	3.76	< .001	0.385	[3.21, 4.31]	Large
Sci. Engagement	2.64	1.97	0.67	< .001	0.356	[0.57, 0.77]	Large

Note. *M* values are covariate-adjusted posttest means. Bonferroni-corrected  $\alpha = .0125$ . All *p*-values are two-tailed. 95% CI refers to the confidence interval for the adjusted mean difference.  $\eta^2p$  = partial eta-squared. Exp. = Experimental group; Ctrl. = Control group.



Note. \*\*\*  $p < .001$ , Bonferroni-corrected.  $\eta^2p$  = partial eta-squared. Scores standardized to 0-100.

**Figure 7.** Univariate ANCOVA Follow-Up: Covariate-Adjusted Mean Comparisons by Group with Significance Indicators.



**Figure 8.** Pretest-Posttest Score Trajectories for Experimental (Left) and Control (Right) Groups Across All Four Dependent Variables.

### Discriminant Function Analysis

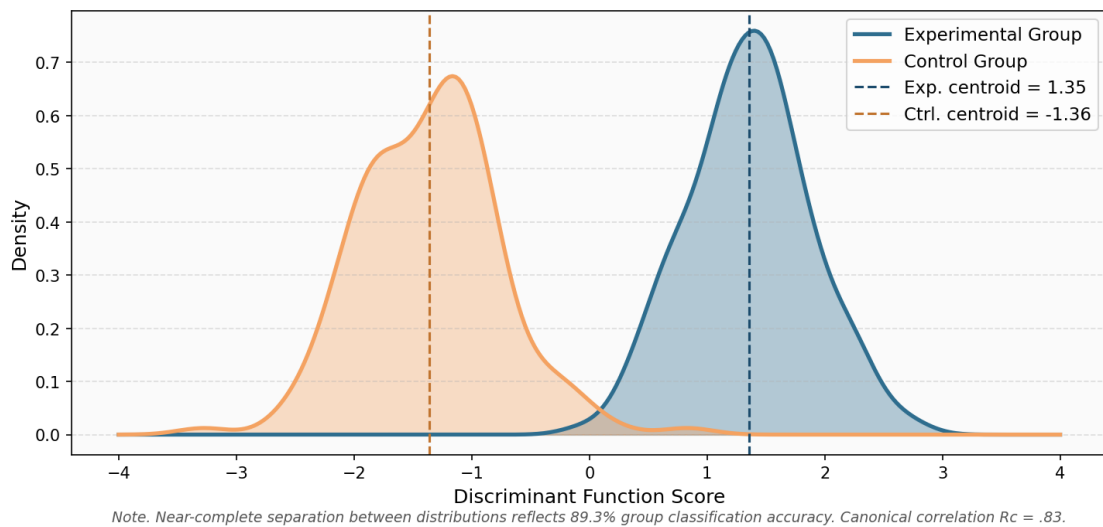
To extend interpretation beyond which outcomes differed between groups, discriminant function analysis (DFA) was conducted on the posttest outcome vector (Huberty & Morris, 1989). DFA produced a single discriminant function, which was statistically significant, Wilks'  $\Lambda = 0.312$ ,  $\chi^2(4) = 348.77$ ,  $p < .001$ , and correctly classified 89.3% of participants into their respective learning condition group substantially exceeding the 50% chance baseline. The canonical correlation was  $R_c = 0.83$ , indicating that the four-variable linear composite accounted for 68.9% of the variance in group classification.

Standardized discriminant function coefficients and structure coefficients are presented in Table 5 and the score distributions visualized in Figure 9. STEM interest exhibited the highest structure coefficient ( $r_s = 0.79$ ) and the largest standardized coefficient (0.84), identifying it as the variable most powerfully associated with the dimension distinguishing hands-on electronics learners from conventionally taught students. Curiosity contributed the second-largest structure coefficient ( $r_s = 0.76$ ), followed by problem-solving ( $r_s = 0.69$ ) and scientific engagement ( $r_s = 0.64$ ). This pattern confirms that the discriminant function primarily reflects a motivational dimension anchored by STEM interest and curiosity, supplemented by cognitive and behavioral outcomes consistent with interest development theory's proposition that motivational constructs are most sensitive to novel, hands-on STEM experiences (Hidi & Renninger, 2006; Renninger & Hidi, 2016).

**Table 6.** Discriminant Function Analysis: Standardized Coefficients, Structure Coefficients, and Communalities

Variable	Std. Coeff.	Structure Coeff.	Communality	Interpretation
STEM Interest	0.84	0.79	0.81	Highest discriminator
Curiosity	0.81	0.76	0.78	Strong discriminator
Problem Solving	0.73	0.69	0.71	Moderate-strong
Sci. Engagement	0.68	0.64	0.66	Moderate discriminator

Note. Structure coefficients ( $r_s$ ) represent the bivariate correlation between each dependent variable and the discriminant function score. Community = proportion of variance accounted for by the discriminant function. Classification accuracy = 89.3%; canonical correlation  $R_c = .83$ .



**Figure 9.** Kernel Density Distribution of Discriminant Function Scores for Experimental (Teal) and Control (Amber) Groups.

### ***Educational Interpretation of Findings***

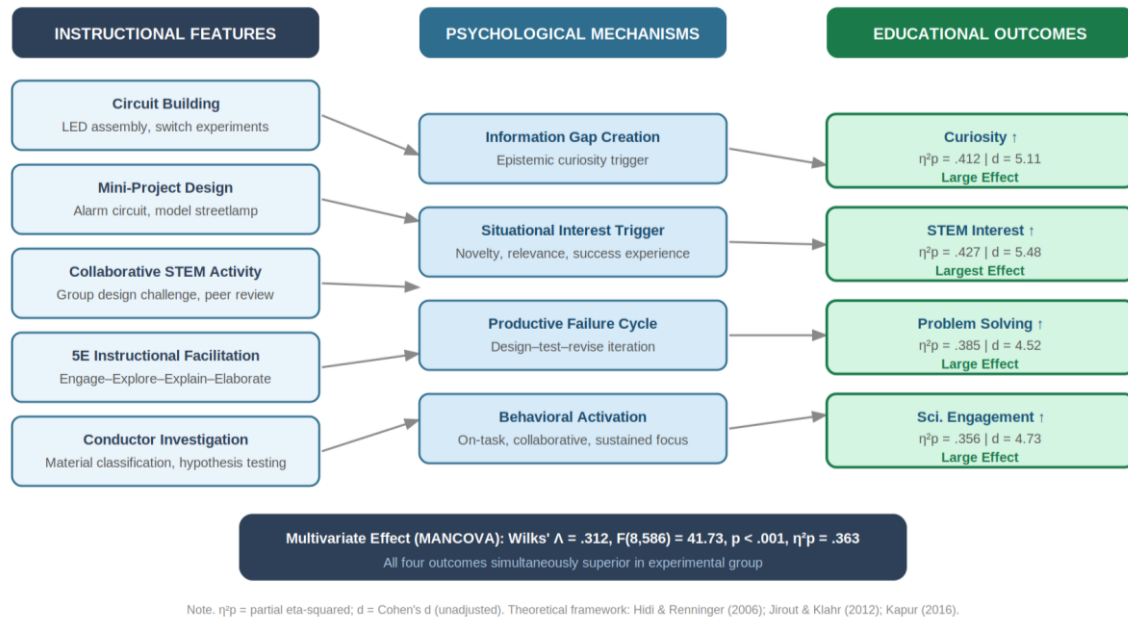
Taken in concert, the multivariate and univariate findings provide convergent and robust evidence that participation in a structured, eight-session hands-on electronics learning program produced statistically significant and practically large improvements across all four targeted educational outcomes relative to conventional instruction. The breadth of the multivariate effect spanning motivational (curiosity, STEM interest), cognitive (problem-solving), and behavioral (scientific engagement) domains simultaneously is theoretically consistent with the integrative educational affordances of well-designed, project-based STEM activities (Krajcik & Shin, 2022; Han et al., 2021).

The finding that STEM interest registered the largest univariate effect ( $\eta^2 p = .427$ ) and served as the primary discriminating variable in the DFA carries particular developmental significance. Interest development theory posits that situational interest triggered by novelty, personal relevance, social support, and success experiences can catalyze the transition toward stable individual interest when students experience repeated positive outcomes in a domain (Hidi & Renninger, 2006). The hands-on electronics program deliberately incorporated each of these situational interest triggers, and the large effect on STEM interest observed in the present study suggests that this combination was highly effective at shifting children's affective orientation toward STEM an outcome with documented longitudinal predictive value for STEM career aspirations (Master et al., 2021; Sahin et al., 2021).

The large effect on scientific curiosity ( $\eta^2 p = .412$ ) is interpretable through epistemic curiosity theory (Litman, 2008; Jirout & Klahr, 2012). The circuit-building and conductor-investigation activities systematically created and resolved information gaps a core curiosity-generation mechanism identified by Loewenstein (1994). The productive failure dynamic inherent in iterative circuit design (Kapur, 2016) appears to have been particularly potent for curiosity stimulation, consistent with Oppermann et al.'s (2021) longitudinal evidence that hands-on physical science experiences are among the strongest predictors of sustained scientific curiosity in elementary students. The significant effect on problem-solving skills ( $\eta^2 p = .385$ ) reflects the cognitive gains associated with the design-and-test cycles embedded within project-based sessions. Finally, the large effect on scientific engagement ( $\eta^2 p = .356$ ) underscores the behavioral and affective investment that hands-on electronics activities generated consistent with evidence that tangible, artefact-producing learning contexts sustain on-task behavior and

metacognitive monitoring across extended instructional sequences (Fredricks et al., 2004; Blikstein, 2013).

The educational process infographic (Figure 10) synthesizes these mechanisms, mapping instructional features of the intervention to their hypothesized psychological mechanisms and associated outcome effects. Figure 11 provides a session-by-session heatmap of scientific engagement observer ratings, illustrating a clear ascending trajectory across the eight intervention sessions, with peak engagement density recorded during Sessions 5–6 (prototype construction) and sustained high levels during Sessions 7–8 (presentation and reflection) phases that placed the greatest demands on collaborative problem-solving and self-presentation competencies.



**Figure 10.** Educational Process Infographic: Theoretical Mechanism Linking Hands-On Electronics Learning to Four Educational Outcomes.



**Figure 11.** Session-by-Session Engagement Heatmap for the Experimental Group (N = 150) Across Three Engagement Dimensions.

**Discussion**

The findings of this study provide compelling multivariate evidence that structured hands-on electronics learning produces simultaneous and large improvements across four educationally significant outcome dimensions among elementary school students. The omnibus MANCOVA result (Wilks'  $\Lambda = .312$ ,  $\eta^2p = .363$ ) confirms that the intervention's advantage over conventional instruction is not confined to any single domain but constitutes a broad, multidimensional effect

encompassing scientific curiosity, STEM interest, problem-solving skills, and scientific engagement. This pattern is theoretically coherent: from an experiential learning perspective (Kolb, 1984), physically engaging STEM activities generate a self-reinforcing learning cycle in which direct experience stimulates reflective observation, which in turn deepens conceptual understanding and motivates further active experimentation. The convergence of large effects across motivational, cognitive, and behavioral outcomes simultaneously rather than isolated improvements on a single measure suggests that hands-on electronics learning activates the integrated architecture of scientific competence in a manner that conventional, text-centered instruction does not (Krajcik & Shin, 2022; Blikstein, 2013).

The differential effects across the four dependent variables offer theoretically instructive insights. The largest univariate effect was observed for STEM interest ( $\eta^2p = .427$ ), followed closely by curiosity ( $\eta^2p = .412$ ), with problem-solving and engagement producing comparably large but slightly smaller effects. This ordering aligns with interest development theory (Hidi & Renninger, 2006), which positions motivational constructs as the most immediate and sensitive responses to novel, personally meaningful STEM experiences, and with discriminant function analysis results identifying STEM interest and curiosity as the primary variables differentiating the two groups. The circuit-building and mini-project activities systematically incorporated the four triggers of situational interest identified by Hidi and Renninger: novelty, personal relevance, social support, and mastery experience explaining the particular potency of the intervention for motivational outcomes. The problem-solving gains, meanwhile, are attributable to the productive failure dynamic (Kapur, 2016) inherent in circuit troubleshooting: students who encountered malfunctioning prototypes were required to diagnose, hypothesize, and iteratively revise a process structurally isomorphic to engineering design reasoning that transfers beyond the specific circuit context to generalized problem-solving competence (Jonassen, 2011). Collectively, these findings extend the work of Oppermann et al. (2021) and Nguyen et al. (2022) by demonstrating that electricity-based hands-on learning in an Indonesian elementary context replicates and amplifies the motivational and cognitive gains documented in more resource-abundant educational settings.

The practical implications of these findings are directly actionable for multiple stakeholder groups. For teachers, the study demonstrates that the 5E instructional model, combined with low-cost modular electronics kits, provides a feasible and evidence-based framework for implementing hands-on STEM instruction without requiring specialist engineering expertise—a particularly relevant finding for the Indonesian elementary context undergoing rapid pedagogical transformation under the Merdeka Belajar curriculum (Kemendikbud, 2022). For curriculum developers, the evidence supports systematic integration of electronics-based project activities into the Grade 4–6 physical science curriculum, as the observed motivational gains at this developmental stage carry documented predictive value for secondary STEM course selection and long-term career aspirations (Master et al., 2021; Wang et al., 2024). For policymakers, the study provides a quantitative rationale for investment in hands-on STEM resources and inquiry-oriented professional development as instruments of systemic reform, particularly given that the total material cost of the intervention kit is financially accessible within standard district-level school budgets. These implications extend beyond the Indonesian context to any educational system in which conventional, textbook-centered elementary science instruction remains the dominant pedagogical mode.

Notwithstanding its contributions, the study carries several limitations that bound the scope of its conclusions and point toward productive future research. The restriction of the sample to Lakarsantri District, Surabaya, limits external validity with respect to more rural or resource-constrained school contexts, and the quasi-experimental design necessitated by the ethical and logistical constraints of primary school research precludes definitive causal inference. The four-week intervention duration, while sufficient to produce the observed immediate effects, provides no evidence regarding the long-term sustainability of curiosity and STEM interest gains, which may be partially attributable to novelty effects that attenuate as electronics activities

become familiar. Future research should prioritize longitudinal designs tracking motivational and cognitive trajectories from elementary through secondary school among students with early hands-on electronics experience, as well as cross-cultural comparative studies examining whether the observed effects replicate across educational systems with different curricular traditions. The integration of programmable robotics platforms, AI-assisted inquiry environments, and digital fabrication tools into the hands-on learning framework evaluated here represents a particularly promising extension that warrants empirical investigation, as these technologies may amplify the curiosity and problem-solving outcomes observed in the present study while simultaneously developing the computational thinking competencies increasingly demanded by 21st-century STEM fields (Wing, 2006; Bers et al., 2023). Structural equation modeling approaches in future studies would additionally enable researchers to test the causal pathways among the four outcome constructs for instance, whether curiosity mediates the relationship between hands-on engagement and STEM interest thereby advancing from the multivariate pattern documented here toward a theoretically specified and empirically validated causal model of elementary electronics learning.

## CONCLUSION

This study demonstrates that structured hands-on electronics learning significantly enhances elementary students' scientific curiosity, STEM interest, problem-solving skills, and scientific engagement compared with conventional science instruction. The large multivariate effect confirmed through MANCOVA indicates that the intervention did not merely improve isolated learning outcomes, but strengthened a broader profile of motivational, cognitive, and behavioral STEM competencies. Discriminant function analysis further showed that STEM interest and scientific curiosity were the strongest dimensions distinguishing students who experienced hands-on electronics learning from those who received conventional instruction, suggesting that tangible, inquiry-oriented, and artefact-producing activities are particularly powerful in stimulating children's affective orientation toward STEM. These findings contribute to elementary STEM education by providing empirical support for integrating low-cost electronics-based activities into primary science curricula, especially in contexts where science learning remains dominated by textbook-based approaches. Practically, the study highlights the need for teacher professional development, curriculum support, and accessible learning media that enable students to explore electricity through direct manipulation, collaboration, experimentation, and reflection. However, the study is limited by its quasi-experimental design, short intervention duration, and sample drawn from one district in Surabaya, which may restrict the generalizability and long-term interpretation of the findings. Future research should employ longitudinal, randomized, and cross-contextual designs to examine the sustainability of students' curiosity, STEM interest, and problem-solving development, while also exploring the integration of robotics, digital fabrication, and AI-supported inquiry environments into elementary electronics learning.

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