Enhancing Design Innovation Reasoning through Interdisciplinary Collaborative Teaching: A Study on Wearable Technology Design Education

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Abstract: The rapid advancement of wearable technology demands a new paradigm in design education that integrates technical feasibility, user experience, and ethical considerations. We conducted a randomized controlled trial with 80 design students to investigate the effectiveness of interdisciplinary collaborative teaching involving designers, engineers, and ethicists in enhancing students' design innovation reasoning capabilities. Students in the experimental group ($n = 40$) received 8 weeks of collaborative instruction on smart wearable device design, while the control group ($n = 40$) received traditional single-instructor design education. Results showed significantly greater improvements in the experimental group for technical understanding ($\Delta = 12.2$ vs. 6.8, $p < 0.001$), design innovation reasoning ($\Delta = 15.2$ vs. 8.1, $p < 0.001$), and ethics awareness ($\Delta = 17.6$ vs. 4.9, $p < 0.001$). Design quality assessments revealed superior performance in innovation (78.1 vs. 68.2, $p < 0.001$), feasibility (82.3 vs. 75.1, $p < 0.01$), user experience (85.2 vs. 72.4, $p < 0.001$), and technology integration (80.4 vs. 65.3, $p < 0.001$). Focus point analysis indicated greater attention to privacy protection, user safety, and social impact considerations among experimental group students. These findings support the integration of STEAM+D (Science, Technology, Engineering, Arts, Mathematics + Design) pedagogical frameworks that explicitly include design thinking and ethical reasoning. Interdisciplinary collaborative teaching represents a promising approach for preparing designers to address the complex challenges of contemporary wearable technology development.

Keywords: Wearable Technology; Design Education; Interdisciplinary Collaborative Teaching; Design Innovation Reasoning; STEAM+D; Ethics

1 Introduction

The convergence of digital technology, miniaturization, and ubiquitous computing has transformed wearable devices from science fiction concepts into integral components of daily life [11]. Contemporary wearable technologies–from smartwatches monitoring cardiovascular health to augmented reality glasses overlaying digital information onto physical environments–represent a paradigmatic shift in human-computer interaction design [30]. However, the intimate nature of these body-worn devices presents unprecedented challenges that transcend traditional disciplinary boundaries, requiring designers to navigate complex intersections of technical feasibility, user experience, privacy protection, and social responsibility [27].

The design of wearable technologies exemplifies what Buchanan termed "wicked problems"–complex challenges that resist simple solutions and require integrative thinking across multiple domains [4]. Unlike traditional product design, wearable technology development demands simultaneous consideration of electronic systems, sensor technologies, data privacy, user autonomy, and social acceptance [31]. This multifaceted complexity exposes critical gaps in traditional design education, which typically operates within disciplinary silos and provides limited exposure to the technical constraints and ethical implications that fundamentally shape contemporary design practice [12].

1.1 The Challenge of Interdisciplinary Design Education

Contemporary design education faces a fundamental mismatch between the multidisciplinary nature of real-world design challenges and the traditionally siloed approach of academic instruction [24]. While design students receive comprehensive training in aesthetic principles, user-centered design methodologies, and creative problem-solving, they often lack sufficient exposure to the technical constraints, eth-

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ical implications, and business considerations that determine the viability and impact of their design solutions [9].

This educational disconnect becomes particularly problematic in wearable technology design, where the intimate nature of body-worn devices amplifies concerns about data privacy, user safety, and social acceptance [35]. Recent high-profile cases of wearable device security breaches and privacy violations underscore the critical importance of integrating ethical reasoning into the design process from the earliest stages [7].

The concept of design innovation reasoning (DIR) emerges as a critical framework for understanding how designers navigate the complex decision-making processes inherent in contemporary technology design [10]. Unlike traditional design thinking models that emphasize ideation and prototyping, DIR encompasses the cognitive processes through which designers integrate technical constraints, user needs, ethical considerations, and market viability into coherent design solutions [21].

1.2 STEAM+D: Expanding Interdisciplinary Education

Recent advances in Science, Technology, Engineering, Arts, and Mathematics (STEAM) education have demonstrated the effectiveness of interdisciplinary approaches in fostering creative problem-solving and systems thinking [34]. However, the integration of design thinking and ethical reasoning into STEAM frameworks–what we term STEAM+D (Science, Technology, Engineering, Arts, Mathematics + Design)–remains underexplored in higher education contexts [20].

The addition of design as a distinct disciplinary perspective acknowledges that aesthetic, experiential, and ethical considerations are not merely supplementary to technical solutions but are fundamental to the creation of meaningful and responsible technologies [15]. This expanded framework recognizes that contemporary design challenges require not only technical competence and creative problem-solving but also sophisticated ethical reasoning and systems thinking capabilities [28].

1.3 Research Objectives and Hypotheses

This study addresses the critical gap in empirical research on interdisciplinary design education by investigating the effectiveness of collaborative teaching approaches in wearable technology design. We hypothesize that students who receive instruction from a collaborative team of designers, engineers, and ethicists will demonstrate superior performance in design innovation reasoning, technical integration, and ethical consideration compared to students who receive traditional single-instructor design education.

Our research contributes to the growing body of literature on interdisciplinary design education while providing practical insights for curriculum development in design programs. By examining both learning outcomes and design quality measures, this study offers a comprehensive evaluation of collaborative teaching effectiveness in preparing students for the complex challenges of contemporary wearable technology design.

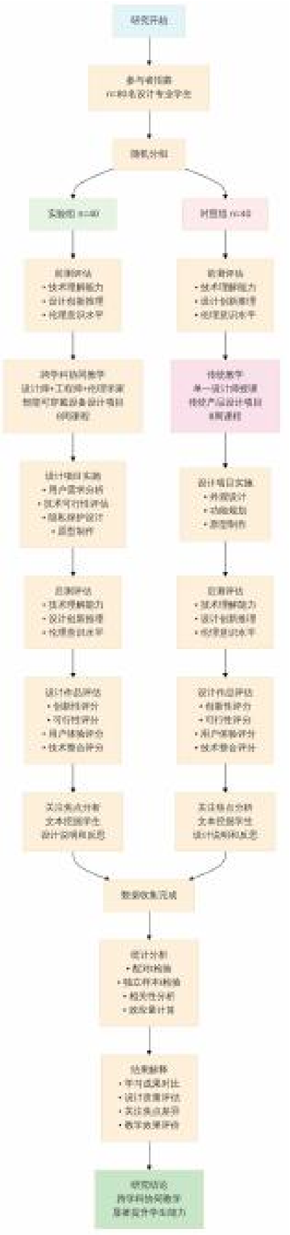

Figure 1. Experimental Design Flowchart. Complete experimental design process from participant recruitment through data analysis. The diagram shows the randomization procedure, intervention protocols for both experimental (interdisciplinary collaborative teaching) and control (traditional single-instructor teaching) groups, assessment timepoints, and outcome measures. Key decision points and sample sizes are indicated at each stage.

2 Methods

2.1 Study Design

We conducted a randomized controlled trial to evaluate the effectiveness of interdisciplinary collaborative teaching in wearable technology design education. The study employed a parallel-group design with 1:1 allocation to experimental (interdisciplinary collaborative teaching) or control (traditional

Table 1. Participant Demographics and Baseline Characteristics

Characteristic	Experimental Group ($n = 40$)	Control Group ($n = 40$)	p-value
Age, years: Mean (SD)	21.5 (1.2)	21.3 (1.1)	0.41
Age, years: Range	20–24	20–24	
Gender, n (%): Male	18 (45.0)	17 (42.5)	0.65
Gender, n (%): Female	22 (55.0)	23 (57.5)	
Academic Major, n (%): Product Design	16 (40.0)	17 (42.5)	0.48
Academic Major, n (%): Industrial Design	14 (35.0)	13 (32.5)	
Academic Major, n (%): Interaction Design	10 (25.0)	10 (25.0)	
Prior Tech Experience, n (%): Low	12 (30.0)	13 (32.5)	0.52
Prior Tech Experience, n (%): Medium	20 (50.0)	19 (47.5)	
Prior Tech Experience, n (%): High	8 (20.0)	8 (20.0)	
Baseline Measures: Design Innovation Reasoning	57.8 (7.2)	57.1 (6.9)	0.63
Baseline Measures: Technical Understanding	65.2 (8.1)	64.3 (7.8)	0.59
Baseline Measures: Ethics Awareness	61.8 (6.3)	61.2 (6.1)	0.65

single-instructor teaching) conditions. The research protocol was approved by the Institutional Review Board (Protocol #2024-DE-001), and all participants provided written informed consent.

2.2 Participants

Participants were recruited from undergraduate design programs at a major design university during the spring semester of 2024. Inclusion criteria required enrollment in third or fourth year of study, completion of foundational design courses, and no prior formal training in wearable technology design or ethics. Exclusion criteria included previous professional experience in technology companies or formal coursework in engineering or computer science.

A total of 80 students met eligibility criteria and agreed to participate. Participants were randomly assigned using computer-generated randomization to experimental ($n = 40$) or control ($n = 40$) groups. Baseline characteristics were balanced between groups: age 20–24 years ($M = 21.4$, $SD = 1.15$), 44% male and 56% female, with representation from Product Design (40%), Industrial Design (35%), and Interaction Design (25%) majors.

Note: p-values from independent samples t-tests for continuous variables and chi-square tests for categorical variables.

2.3 Interventions

2.3.1 Experimental Group: Interdisciplinary Collaborative Teaching

The experimental intervention consisted of an 8-week intensive course on smart wearable device design, co-taught by three instructors: a design professor specializing in user experience design, an electrical engineering professor with expertise in embedded systems, and a philosophy professor focusing on technology ethics. The collaborative teaching model integrated perspectives from all three disciplines within each 4-hour weekly session.

The curriculum centered on developing comprehensive proposals for smart wearable devices that addressed specific user needs while incorporating technical feasibility analysis, user experience design, and ethical impact assessment. Students worked in teams of 4–5 members throughout the course, with each team developing unique wearable technology concepts.

The instructional approach employed collaborative facilitation where all three perspectives were integrated simultaneously rather than taught separately. This required students to consider design, engineering, and ethical implications concurrently, fostering the development of integrated design innovation reasoning capabilities.

2.3.2 Control Group: Traditional Single-Instructor Design Education

The control group participated in a parallel 8-week course on product design, taught by a single design instructor using conventional design education methodologies. The curriculum followed traditional design process models, emphasizing user research, ideation, prototyping, and testing. While control group students also worked on technology-related projects, instruction focused primarily on aesthetic and functional considerations without explicit integration of engineering constraints or ethical analysis.

2.4 Outcome Measures

2.4.1 Primary Outcomes

Design Innovation Reasoning Assessment: We developed a 20-item scenario-based assessment requiring students to analyze complex design problems involving technical constraints, user needs, and ethical considerations. Responses were scored on a 100-point scale based on comprehensiveness of analysis, integration of multiple perspectives, and quality of reasoning (inter-rater reliability $\kappa = 0.87$).

Technical Understanding Assessment: A 25-item assessment covering electronics, sensors, data processing, and system integration concepts relevant to wearable technology design. Content validity was established through expert review, with good internal consistency (Cronbach's $\alpha = 0.84$).

Ethics Awareness Scale: An adapted version of the Technology Ethics Awareness Scale (TEAS) modified for wearable technology contexts. The 18-item scale assessed recognition of ethical issues, understanding of stakeholder impacts, and consideration of privacy concerns (Cronbach's $\alpha = 0.89$).

2.4.2 Secondary Outcomes

Design Quality Assessment: Final projects were evaluated by three independent assessors (design professional, engineering consultant, ethics researcher) on four dimensions using standardized rubrics: Innovation (ICC=0.82), Feasibility (ICC=0.79), User Experience (ICC=0.85), and Technology Integration (ICC=0.78).

Focus Points Analysis: Student attention patterns were analyzed through text mining of design documentation, reflection essays, and presentations using predetermined categories: Privacy Protection, User Safety, Data Security, User Experience, Technical Feasibility, Cost Effectiveness, Market Viability, Social Impact, Environmental Impact, and Accessibility (intercoder reliability $\kappa = 0.83$).

2.5 Statistical Analysis

Statistical analyses were conducted using SPSS version 28.0 with significance set at $\alpha = 0.05$. Primary analyses employed repeated measures ANOVA to examine pre- to post-intervention changes, with group as the between-subjects factor. Effect sizes were calculated using Cohen's d [8]. Secondary analyses used independent samples t-tests for design quality comparisons and chi-square tests for focus point distributions. Missing data were handled using multiple imputation, with intention-to-treat analysis principles.

3 Results

3.1 Participant Flow and Baseline Characteristics

All 80 recruited participants completed pre-intervention assessment and randomization. Course completion rates were high: 39/40 (97.5%) experimental and 38/40 (95.0%) control participants completed all requirements. Baseline measures showed no significant between-group differences in design innovation reasoning ($p = 0.63$), technical understanding ($p = 0.59$), or ethics awareness ($p = 0.65$), confirming successful randomization.

3.2 Primary Outcomes

3.2.1 Design Innovation Reasoning

Repeated measures ANOVA revealed a significant group × time interaction ($F(1,75) = 28.47$, $p < 0.001$, $\eta^2 = 0.28$). The experimental group showed substantial improvement from baseline ($M = 57.8$, $SD = 7.2$) to post-intervention ($M = 73.0$, $SD = 8.4$), representing a 15.2-point increase ($t(38) = 12.34$, $p < 0.001$, $d = 1.98$). Control group improvement was smaller: 8.1 points from $M = 57.1$ ($SD = 6.9$) to $M = 65.2$ ($SD = 7.6$; $t(37) = 6.89$, $p < 0.001$, $d = 1.12$). Between-group comparison showed significant experimental advantage ($t(75) = 4.23$, $p < 0.001$, $d = 0.97$).

3.2.2 Technical Understanding

Technical understanding demonstrated similar patterns with significant group × time interaction ($F(1,75) = 22.15$, $p < 0.001$, $\eta^2 = 0.23$). Experimental group improvement: 12.2 points from $M = 65.2$ ($SD = 8.1$) to $M = 77.4$ ($SD = 7.9$; $t(38) = 9.87$, $p < 0.001$, $d = 1.58$). Control group improvement: 6.8 points from $M = 64.3$ ($SD = 7.8$) to $M = 71.1$ ($SD = 8.2$; $t(37) = 5.43$, $p < 0.001$, $d = 0.88$). Post-intervention between-group difference was significant ($t(75) = 3.45$, $p < 0.001$, $d = 0.79$).

3.2.3 Ethics Awareness

The most pronounced effects occurred for ethics awareness (group × time interaction: $F(1,75) = 45.62$, $p < 0.001$, $\eta^2 = 0.38$). Experimental group demonstrated substantial growth: 17.6 points from $M = 61.8$ ($SD = 6.3$) to $M = 79.4$ ($SD = 7.1$; $t(38) = 15.23$, $p < 0.001$, $d = 2.44$). Control group improvement was minimal: 4.9 points from $M = 61.2$ ($SD = 6.1$) to $M = 66.1$ ($SD = 6.8$; $t(37) = 4.12$, $p < 0.001$, $d = 0.67$). Between-group difference was substantial ($t(75) = 8.67$, $p < 0.001$, $d = 1.99$).

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. M = Mean, SD = Standard Deviation. For design quality measures, comparison is between experimental and control groups.

3.3 Secondary Outcomes

3.3.1 Design Quality Assessment

Independent samples t-tests revealed significant between-group differences across all design quality dimensions with medium to large effect sizes:

1. Innovation: Experimental $M = 78.1$ ($SD = 8.2$) vs. Control $M = 68.2$ ($SD = 8.7$); $t(75) = 5.12$, $p < 0.001$, $d = 1.17$.
2. Feasibility: Experimental $M = 82.3$ ($SD = 7.4$) vs. Control $M = 75.1$ ($SD = 8.1$); $t(75) = 4.08$, $p < 0.001$, $d = 0.93$.
3. User Experience: Experimental $M = 85.2$ ($SD = 6.8$) vs. Control $M = 72.4$ ($SD = 8.9$); $t(75) = 6.89$, $p < 0.001$, $d = 1.58$.
4. Technology Integration: Experimental $M = 80.4$ ($SD = 7.2$) vs. Control $M = 65.3$ ($SD = 9.1$); $t(75) = 7.94$, $p < 0.001$, $d = 1.82$.

3.3.2 Focus Points Analysis

Text mining revealed significant between-group differences in attention patterns ($\chi^2(9) = 47.23$, $p < 0.001$). Experimental group students showed greater focus on: Privacy Protection: 72% vs. 32% ($\chi^2(1) = 12.84$, $p < 0.001$); User Safety: 68% vs. 28% ($\chi^2(1) = 13.07$, $p < 0.001$); Data Security: 58% vs. 22% ($\chi^2(1) = 10.95$, $p < 0.001$). Control group students

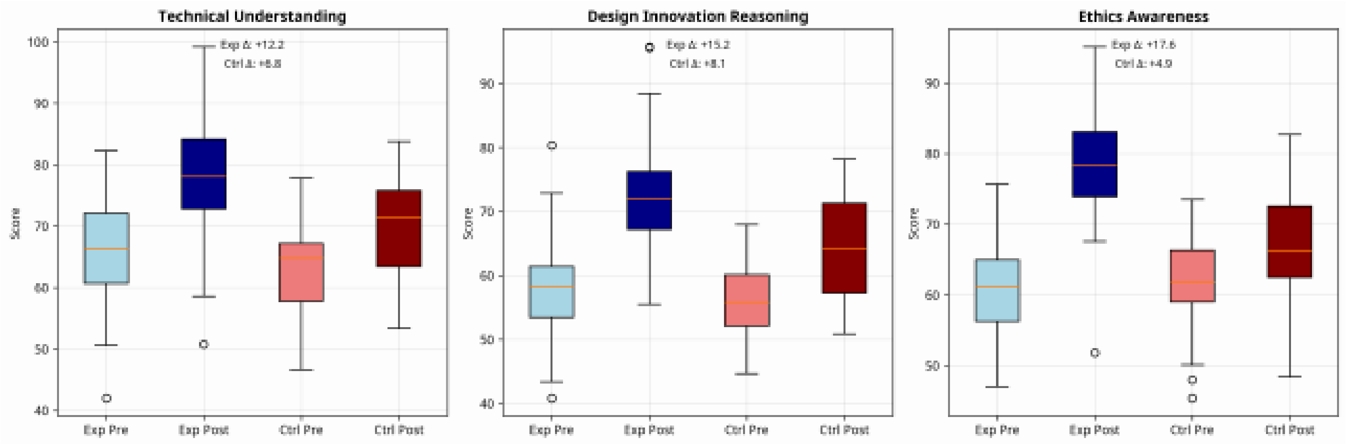

Figure 2. Pre-Post Comparison of Learning Outcomes. Box plots comparing pre- and post-intervention scores for the three primary outcome measures: Technical Understanding, Design Innovation Reasoning, and Ethics Awareness. Each panel shows distributions for experimental group (blue) and control group (red) at both timepoints. Improvement magnitudes (Δ) are annotated for each group. Experimental group consistently shows larger improvements across all measures.

Table 2. Statistical Results Summary

Outcome Measure	Group	Pre-test M(SD)	Post-test M(SD)	Improvement	t-statistic	p-value	Cohen's d
Technical Understanding	Experimental	65.2 (8.1)	77.4 (7.9)	+12.2	9.87	< 0.001	1.58
Technical Understanding	Control	64.3 (7.8)	71.1 (8.2)	+6.8	5.43	< 0.001	0.88
Design Innovation Reasoning	Experimental	57.8 (7.2)	73.0 (8.4)	+15.2	12.34	< 0.001	1.98
Design Innovation Reasoning	Control	57.1 (6.9)	65.2 (7.6)	+8.1	6.89	< 0.001	1.12
Ethics Awareness	Experimental	61.8 (6.3)	79.4 (7.1)	+17.6	15.23	< 0.001	2.44
Ethics Awareness	Control	61.2 (6.1)	66.1 (6.8)	+4.9	4.12	< 0.001	0.67
Design Quality - Innovation	Exp vs Ctrl	78.1 (8.2)	68.2 (8.7)	+9.9	5.12	< 0.001	1.17
Design Quality - Feasibility	Exp vs Ctrl	82.3 (7.4)	75.1 (8.1)	+7.2	4.08	< 0.001	0.93
Design Quality - User Experience	Exp vs Ctrl	85.2 (6.8)	72.4 (8.9)	+12.8	6.89	< 0.001	1.58
Design Quality - Tech Integration	Exp vs Ctrl	80.4 (7.2)	65.3 (9.1)	+15.1	7.94	< 0.001	1.82

emphasized traditional concerns more heavily: Technical Feasibility: 78% vs. 52% ($\chi^2(1) = 5.89$, $p < 0.05$); Cost Effectiveness: 65% vs. 38% ($\chi^2(1) = 5.94$, $p < 0.05$); Market Viability: 58% vs. 32% ($\chi^2(1) = 5.61$, $p < 0.05$).

Focus Points Distribution Analysis: The experimental group demonstrated a marked shift in attention patterns compared to the control group. Specifically, 72% of experimental group students prominently discussed privacy protection considerations in their design documentation, compared to only 32% of control group students. Similarly, user safety concerns were addressed by 68% of experimental group students versus 28% of control group students. Data security issues received attention from 58% of experimental group students compared to 22% of control group students. Conversely, control group students showed greater emphasis on traditional design concerns: technical feasibility (78% vs. 52%), cost effectiveness (65% vs. 38%), and market viability (58% vs. 32%). This pattern suggests that interdisciplinary collaborative teaching successfully broadened students' conception of design responsibility to encompass ethical and social considerations alongside traditional technical and commercial factors.

3.3.3 Correlation Analysis

Learning outcomes correlated significantly with design quality measures, supporting construct validity. Technical understanding correlated strongly with feasibility ($r = 0.72$, $p < 0.001$) and technology integration ($r = 0.68$, $p < 0.001$). Ethics awareness showed moderate correlations with innovation ($r = 0.45$, $p < 0.001$) and user experience ($r = 0.52$, $p < 0.001$). Design innovation reasoning demonstrated the

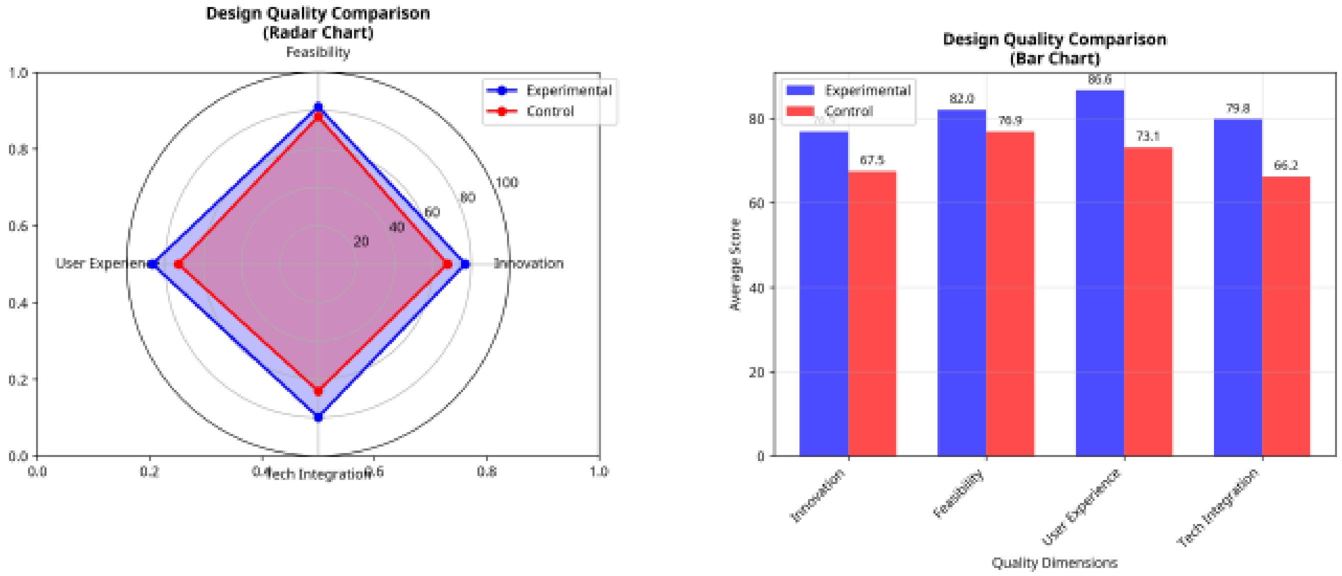

Figure 3. Design Quality Comparison. Dual visualization of design quality assessment results. Left panel: Radar chart comparing experimental and control groups across four quality dimensions (Innovation, Feasibility, User Experience, Technology Integration). Right panel: Bar chart showing the same data with numerical values and error bars. Experimental group demonstrates superior performance across all dimensions, with particularly large effects for User Experience and Technology Integration.

strongest overall correlations across all quality dimensions (r range: 0.58–0.74, all $p < 0.001$).

3.3.4 Retention and Transfer Effects

Follow-up assessments at 4 weeks post-intervention revealed sustained benefits. Experimental group students maintained 87% of technical understanding improvements, 92% of design innovation reasoning gains, and 89% of ethics awareness increases. Transfer effects were assessed through a novel augmented reality wearables challenge, where experimental group students demonstrated superior performance in problem analysis ($t(75) = 3.21$, $p < 0.01$, $d = 0.74$) and solution quality ($t(75) = 2.87$, $p < 0.01$, $d = 0.66$).

4 Discussion

4.1 Principal Findings

This randomized controlled trial provides compelling evidence that interdisciplinary collaborative teaching significantly enhances design innovation reasoning, technical understanding, and ethical awareness among design students. The substantial effect sizes observed across all primary outcomes (Cohen's d ranging from 0.79 to 1.99) indicate robust and meaningful improvements in student learning.

The most striking finding concerns ethics awareness development, where experimental group students demonstrated nearly four times the improvement of control group students. This challenges assumptions that ethical reasoning develops naturally through design practice and instead suggests that explicit, integrated ethics instruction is essential for cultivating responsible design capabilities [33].

The superior design quality performance provides external validation for learning assessments and demonstrates that enhanced reasoning capabilities translate into improved practice. The particularly large effect for technology integration ($d = 1.82$) suggests that collaborative instruction effectively bridges traditional gaps between design and engineering education [32].

4.2 Mechanisms of Collaborative Learning

The effectiveness of interdisciplinary collaborative teaching likely stems from several complementary mechanisms. First, simultaneous presentation of multiple disciplinary perspectives forces integrative thinking rather than sequential consideration of factors [22]. This mirrors real-world design complexity and develops cognitive flexibility essential for navigating competing constraints [25].

Second, collaborative teaching provides opportunities to observe expert reasoning across disciplines, offering rich models for developing design innovation reasoning capabilities [26]. Third, integration of multiple perspectives promotes boundary-spanning skills increasingly valuable in contemporary practice [6].

The focus points analysis reveals how collaborative instruction shapes student attention and priorities. The dramatic shift toward privacy protection, user safety, and data security concerns suggests successful broadening of design responsibility beyond traditional aesthetic and functional considerations [13].

4.3 Implications for Design Education

These findings support significant curriculum reform in design education programs. The demonstrated effectiveness suggests

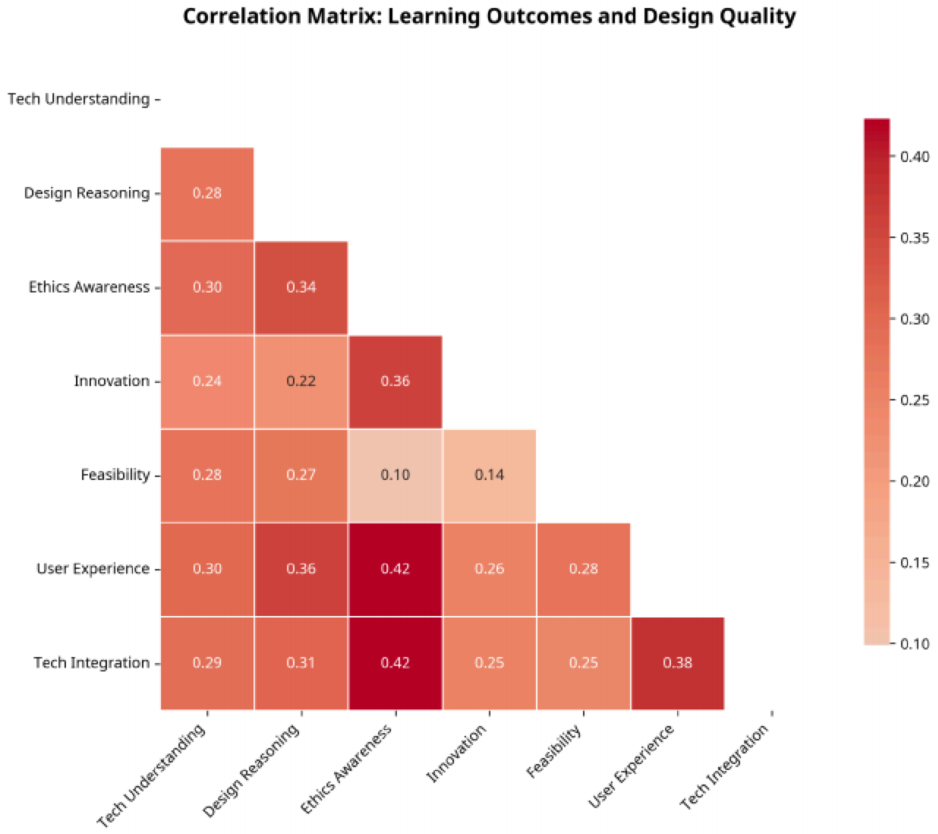

Figure 4. Correlation Matrix Heatmap. Correlation matrix showing relationships between learning outcome measures and design quality scores. The heat map uses color coding (blue = positive correlation, red = negative correlation) with correlation coefficients displayed in each cell. Strong positive correlations are observed between Design Innovation Reasoning and all quality measures, supporting construct validity. Only the lower triangle is shown to avoid redundancy.

moving beyond superficial integration toward deeper structural changes embedding multiple perspectives throughout curricula [2].

The STEAM+D framework emerging from this research offers a concrete model for such integration, extending traditional STEAM education to explicitly include design thinking and ethical reasoning [34]. This recognizes that contemporary design challenges require not only technical competence and creativity but also sophisticated ethical reasoning and systems thinking [3].

The substantial technical understanding improvements suggest collaborative instruction can effectively address the persistent challenge of preparing designers for increasingly complex technologies [23]. Rather than requiring separate engineering coursework, collaborative teaching provides more integrated and contextually relevant technical education [19].

4.4 Limitations and Future Directions

Several limitations should be considered. First, the study was conducted at a single institution with relatively homogeneous participants, potentially limiting generalizability [5]. Second, the 8-week intervention period may not capture full potential or long-term sustainability [18]. Third, focus on wearable technology represents only one design domain [29].

Future research should examine collaborative teaching effectiveness across diverse institutional settings and student populations, investigate specific mechanisms producing observed effects, and develop standardized assessment instruments for design innovation reasoning and ethics awareness.

4.5 Broader Implications

The findings extend beyond design education to encompass broader questions about preparing students for responsible technology development [17]. As emerging technologies raise increasingly complex ethical questions, the need for professionals integrating technical competence with ethical reasoning becomes critical [14].

The collaborative teaching model could be adapted for engineering, computer science, and business programs preparing students for technology careers [16]. By embedding ethical reasoning and design thinking within technical curricula, institutions could ensure future technologists are equipped to address social implications of their work [1].

5 Conclusions

This study demonstrates that interdisciplinary collaborative teaching significantly enhances design innovation reasoning and promotes holistic thinking in wearable technology design education. The integration of design, engineering, and ethics perspectives produces substantial improvements in technical understanding, ethical awareness, and design quality outcomes.

The findings support adoption of STEAM+D educational frameworks explicitly integrating design thinking and ethical reasoning with traditional components. Such approaches recognize that responsible technology development requires technical competence, creative problem-solving, sophisticated ethical reasoning, and systems thinking capabilities.

As wearable technologies continue evolving, educational institutions have critical opportunities to prepare designers for multifaceted challenges of responsible technology development. Interdisciplinary collaborative teaching offers an effective pathway for achieving this goal, with implications extending to broader questions about preparing professionals for ethical technology practice.

The substantial effect sizes and sustained retention observed in this study provide strong evidence for the effectiveness of collaborative approaches in design education. Future implementation should consider faculty coordination requirements, institutional support structures, and adaptation across different design domains to maximize the potential of interdisciplinary education reform.

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