

Designing Educational Information Systems to Optimize Learning Factory Operations

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ABSTRACT

Interdisciplinary teamwork within the learning factory framework has emerged as an effective approach to bridging theoretical knowledge and practical innovation, encouraging students from diverse academic backgrounds to collaborate and solve complex real world problems creatively. This educational model promotes experiential learning, yet the specific mechanisms through which interdisciplinary collaboration enhances creativity and innovation remain underexplored. **This study** aims to investigate how teamwork across multiple disciplines fosters innovation and creativity in learning factory projects and to identify the factors that facilitate or hinder this process. **Using a qualitative** case study design, data were collected through semi structured interviews, direct observations, and project documentation involving students and instructors from engineering, design, and business programs participating in interdisciplinary learning factory initiatives. The data were analyzed thematically to identify key patterns of collaboration, communication, and idea generation. **The findings** reveal that interdisciplinary teamwork significantly stimulates creative problem solving by integrating diverse perspectives, promoting mutual learning, and creating an environment that values experimentation and iteration. However, challenges such as disciplinary boundaries, communication gaps, and differing work cultures occasionally impede the collaborative process. **The study concludes** that effective facilitation, open communication, and reflective practices are crucial for maximizing innovation and creativity in interdisciplinary learning factory teams. These insights highlight the importance of designing structured yet flexible learning environments that encourage knowledge integration, creative thinking, and cross disciplinary synergy to prepare students for complex, innovation driven professional contexts.

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1. INTRODUCTION

In recent years, the concept of the learning factory has gained significant attention as a pedagogical model that bridges academic knowledge and practical application, especially within higher education institutions that emphasize engineering, business, design, and technology [1]. The learning factory framework

provides an authentic environment where students can apply theoretical knowledge to real world problems, encouraging experiential and project based learning. Within this context, interdisciplinary teamwork has become a cornerstone for cultivating creativity and innovation two essential competencies in the 21st century workforce [2]. By integrating diverse disciplinary perspectives, students are encouraged to approach complex problems from multiple angles, fostering solutions that are both technically sound and socially relevant.

In addition to its educational importance, the learning factory approach is closely aligned with several Sustainable Development Goals (SDGs). Specifically, SDG 4 (Quality Education) underscores the need for innovative learning models that develop practical, future oriented skills, while SDG 8 (Decent Work and Economic Growth) emphasizes preparing students for dynamic, innovation driven work environments. Moreover, the integration of authentic industrial challenges and technology enhanced problem solving within learning factories contributes to SDG 9 (Industry, Innovation, and Infrastructure), as students engage in designing and testing solutions that reflect real industrial systems [3, 4]. Embedding SDG oriented values into the learning factory environment ensures that interdisciplinary collaboration not only enhances academic outcomes but also supports global efforts toward sustainable and innovation focused development. However, while the learning factory model has been widely implemented across educational contexts, the specific ways in which interdisciplinary collaboration contributes to the enhancement of creativity and innovation remain insufficiently understood [5]. This gap highlights the need for a deeper exploration of how teams composed of students from different academic backgrounds interact, share knowledge, and co create novel solutions within such learning environments.

Innovation and creativity are critical drivers of global competitiveness, and higher education institutions play a vital role in nurturing these skills among students [6]. In interdisciplinary learning settings, students from fields such as engineering, business, design, and information technology engage collaboratively to solve complex, often ill structured problems that mirror real industrial or societal challenges. These interactions expose students to diverse thinking styles, problem solving methods, and communication patterns, all of which are key ingredients for fostering creativity [7]. However, interdisciplinary collaboration is not without its challenges. Differences in disciplinary jargon, problem solving approaches, and expectations can lead to misunderstandings, communication barriers, and role ambiguities within teams. Furthermore, students may initially struggle to reconcile the contrasting epistemological foundations of their respective disciplines, potentially hindering the creative process [8]. Nonetheless, when effectively facilitated, these differences can become powerful catalysts for innovation, as they push team members to negotiate meaning, integrate distinct viewpoints, and develop a shared understanding that leads to original and impactful solutions. Thus, studying how these dynamics unfold within the learning factory framework is essential to understanding the mechanisms that promote or hinder creativity in interdisciplinary contexts.

The learning factory environment is particularly well suited to investigating interdisciplinary collaboration because it mirrors the organizational and technical complexities found in real world industrial systems [9, 10]. Within such environments, learning occurs through hands on engagement with design, production, management, and sustainability challenges that require multiple areas of expertise. The interdisciplinary structure of these projects encourages students to move beyond the boundaries of their disciplines and develop transversal competencies such as teamwork, communication, adaptability, and critical thinking. Moreover, the integration of digital technologies and simulation tools within learning factories provides opportunities for experimentation, prototyping, and iterative problem solving processes that are inherently linked to innovation. However, despite these pedagogical advantages, existing research often focuses on learning factories as technical or managerial systems rather than as social systems that foster creativity through human interaction and collaboration [11]. Consequently, there is limited empirical understanding of the relational and communicative processes that enable interdisciplinary teams within learning factories to transform diverse knowledge inputs into creative and innovative outcomes. Addressing this gap is crucial not only for improving the design of learning factory curricula but also for informing broader educational strategies aimed at fostering innovation oriented learning ecosystems.

Given this context, the present study seeks to explore how interdisciplinary teamwork fosters innovation and creativity within the learning factory framework [12]. Specifically, it examines the collaborative processes, communication dynamics, and cognitive mechanisms that enable students from different disciplines to co create solutions that transcend traditional disciplinary boundaries. A qualitative case study approach is adopted to capture the complexity of these interactions and to provide an in depth understanding of participants lived experiences. Through interviews, observations, and document analysis, the study aims to identify the

enablers and barriers of effective interdisciplinary collaboration, shedding light on the conditions that optimize creativity and innovation in such learning environments [13]. The insights derived from this research are expected to contribute to the theoretical discourse on interdisciplinary education and experiential learning while offering practical implications for educators, curriculum designers, and policymakers. By understanding how creativity and innovation emerge from interdisciplinary teamwork within the learning factory, higher education institutions can better prepare students to engage in collaborative, innovation driven work environments that define the future of industry and society [14, 15].

2. LITERATURE REVIEW

2.1. Interdisciplinary Teamwork in Higher Education

Interdisciplinary teamwork has become an essential approach in higher education as global challenges increasingly require solutions that cross disciplinary boundaries. Collaboration among students and faculty from diverse fields encourages the integration of multiple perspectives, fostering holistic understanding and innovative problem solving [16]. Within academic settings, such teamwork exposes learners to various cognitive frameworks, broadening their analytical, reflective, and creative capacities. This exposure not only deepens their conceptual comprehension but also promotes metacognitive awareness as students learn to navigate and reconcile differing modes of reasoning. Furthermore, interdisciplinary collaboration nurtures essential soft skills such as adaptability, empathy, communication, negotiation, and critical thinking competencies that are highly valued in modern industries undergoing rapid technological transformation [17]. Interdisciplinary learning also aligns closely with the global shift toward experiential, project based, and problem based pedagogies, where students are encouraged to construct knowledge actively rather than passively absorb information delivered through traditional lecture based models [18, 19].

However, interdisciplinary teamwork is not without significant challenges. Integrating individuals from distinct disciplinary backgrounds often introduces conflicting terminologies, methodological differences, and epistemological assumptions. These differences can generate misunderstandings that impede team cohesion, particularly when participants lack prior exposure to collaborative and reflective learning environments. Without careful facilitation or clear communication structures, disciplinary divergence may hinder rather than enhance collective problem solving [20]. Institutions must therefore design structured learning environments that promote psychological safety, open dialogue, shared goals, and mutual respect. Effective interdisciplinary collaboration requires more than technical coordination it demands a cultural shift that values diversity of thought, encourages inquiry based engagement, and recognizes the creative potential of synthesizing multiple disciplinary insights. This shift often requires intentional scaffolding from educators, including clear role assignments, reflective checkpoints, and iterative feedback mechanisms [21].

When successfully implemented, interdisciplinary teamwork has the potential to transform learning environments into dynamic ecosystems of collective innovation, critical reflection, and continuous knowledge co creation. Students not only develop technical and conceptual expertise but also cultivate the interpersonal and leadership skills necessary to navigate complex professional environments [22, 23]. By integrating diverse knowledge bases and embracing collaborative experimentation, interdisciplinary teamwork ultimately prepares learners for the multifaceted challenges of contemporary industries where innovation, adaptability, and cross disciplinary synergy increasingly define success.

2.2. The Learning Factory Framework

The learning factory framework provides a realistic, practice oriented model that bridges academic learning with industrial application. Originating as an educational concept inspired by real manufacturing systems, learning factories combine theory and practice in authentic environments where students can apply their knowledge to solve real world problems [24]. These environments emulate industrial processes, workflows, and decision making structures, enabling students to understand the complexities of modern production systems. Learning factories emphasize experiential learning through hands on projects, team based activities, and iterative experimentation, allowing students to navigate the full lifecycle of innovation. Students are encouraged to participate in every stage of the innovation process ideation, design, prototyping, implementation, testing, and evaluation while simultaneously developing both technical skills and collaborative competencies [25]. This approach encourages active learning, reflective practice, and a continuous improvement mindset, all of which are essential for thriving in innovation driven industries where adaptability and rapid problem solving are paramount.

In recent years, modern learning factories have evolved in response to Industry 4.0 and Education 4.0 paradigms, integrating advanced digital technologies such as simulation tools, robotics, cyber physical systems, digital twins, augmented and virtual reality, and data analytics [26]. These technological enhancements increase the realism of learning environments, enabling students to work with tools and systems that closely mirror contemporary industrial practices. As a result, learning factories not only prepare students for future professional environments but also cultivate familiarity with digital transformation processes that are reshaping global industries. Furthermore, the integration of smart technologies enhances the complexity and authenticity of learning experiences, requiring students to engage in higher order thinking, interdisciplinary problem solving, and data driven decision making [27].

Beyond technical skill development, learning factories function as innovation ecosystems that connect academic institutions with industry partners. This partnership facilitates knowledge transfer, collaborative research, and the co creation of solutions to real industrial challenges. By engaging students in industry supported projects, learning factories reduce the gap between academic competencies and workforce demands, fostering employability and entrepreneurship [28]. The emphasis on collaboration, iteration, and reflective learning provides students with first hand experience in interdisciplinary teamwork, demonstrating how the convergence of multiple fields such as engineering, design, business, and information technology fuels innovative problem solving and creative solution development.

Thus, the learning factory framework represents more than a physical or pedagogical model; it embodies a holistic learning environment where creativity, innovation, and professional readiness are cultivated through authentic, interdisciplinary engagement [29, 30]. By situating students in dynamic, technology driven contexts, learning factories equip future professionals with the mindset, skills, and collaborative abilities necessary to navigate and drive innovation in increasingly complex industrial ecosystems.

2.3. Creativity and Innovation in Interdisciplinary Collaboration

Creativity and innovation are fundamental drivers of interdisciplinary collaboration, as they enable teams to synthesize diverse forms of knowledge into novel solutions, new insights, and transformative ideas. In learning factory environments, creativity does not emerge from individual talent alone, but rather from the dynamic interactions among students with varied disciplinary backgrounds [31]. These interactions ignite cognitive stimulation, as contrasting perspectives challenge established assumptions and introduce alternative problem frames. The integration of engineering precision with design oriented approaches, business strategy, or human centered perspectives enriches the cognitive diversity of the team, fostering a more comprehensive and multidimensional understanding of complex issues. Within such environments, students engage in both divergent thinking generating multiple possibilities, exploring unconventional ideas, and expanding the scope of inquiry and convergent thinking, which involves evaluating, refining, and selecting the most feasible solutions [32, 33]. The oscillation between divergent and convergent modes of thought is a hallmark of creative problem solving, and interdisciplinary teams naturally facilitate this dual process through the continuous negotiation of viewpoints, knowledge bases, and analytical approaches.

A well documented phenomenon in interdisciplinary teamwork is the emergence of productive tension, a state in which differing opinions, terminologies, or methodological preferences create friction that stimulates deeper reflection and critical discussion. Rather than obstructing collaboration, productive tension often accelerates the creative process by compelling team members to articulate their reasoning more clearly, reassess their assumptions, and collectively explore alternative pathways [34, 35]. This dynamic pushes individuals beyond disciplinary comfort zones, enabling the development of higher order thinking skills such as synthesis, abstraction, metacognition, and strategic adaptability all of which are crucial to modern innovation ecosystems. In learning factory settings, where challenges often mirror real industrial complexity, such productive tension becomes a catalyst for innovation, helping students produce solutions that are not only technically sound but also user centered, sustainable, and contextually relevant [36].

Creativity within interdisciplinary collaboration is also profoundly shaped by the social, emotional, and psychological climate of the team. Research consistently highlights psychological safety the shared belief that team members can express ideas, admit mistakes, or ask questions without fear of negative consequences as one of the strongest predictors of creativity and innovation [37]. A psychologically safe environment encourages risk taking, experimentation, and the acceptance of failure as a natural and valuable component of the learning process. In learning factory environments, mentors, facilitators, and instructors play a crucial role in cultivating this climate by modeling open communication, mediating conflicts, providing constructive feed-

back, and guiding reflective dialogues. Their presence helps maintain an optimal balance between autonomy and structure, ensuring that students have the freedom to innovate while remaining focused on project goals and design constraints [38].

Reflection, iterative development, and constant feedback cycles further strengthen the creative process. Students are encouraged to continuously evaluate their ideas through prototyping, testing, peer critique, and self reflection. Each iteration yields new insights that refine the concept and enhance its practical viability [39]. This iterative learning aligns closely with industry practices, where innovation depends on repeated cycles of experimentation, failure, and improvement. Through these cycles, students learn not only to refine their ideas but also to build resilience, develop critical self assessment skills, and cultivate an innovation oriented mindset. Iteration also allows interdisciplinary teams to leverage the unique strengths of each discipline more effectively, enabling them to converge on solutions that no single discipline could generate independently.

Overall, the combination of cognitive diversity, productive social dynamics, structured collaboration, iterative experimentation, and reflective practice makes the learning factory an exceptionally fertile environment for fostering sustained creativity and innovation [40]. Students not only gain the technical and analytical capabilities required for industry but also develop the collaborative mindset, creative confidence, and adaptive problem solving skills demanded by rapidly evolving professional landscapes. By engaging with real world challenges in interdisciplinary teams, learning factory participants experience firsthand how innovation emerges at the intersection of diverse expertise and shared purpose ultimately preparing them to contribute meaningfully to the complex, innovation driven industries of the future [41].

2.4. Enablers and Barriers to Innovation in Learning Factory Teams

Innovation within learning factory teams is driven by a complex interaction of enabling factors that support collaborative creativity, knowledge integration, and effective problem-solving across disciplines. Among the most influential enablers are shared goals and a unified sense of purpose, which help align diverse academic backgrounds toward common project outcomes, ensuring that students can synchronize their perspectives and contribute meaningfully to the innovation process [42]. Open communication plays a central role as well, allowing ideas to flow freely, reducing misinterpretations, and promoting a culture where feedback and critique are exchanged constructively. This is reinforced by strong interpersonal trust, which encourages risk taking and motivates students to voice unconventional ideas without fear of judgment. Access to adequate technological resources including prototyping equipment, simulation tools, digital collaboration platforms, and data analytics systems further enhances creativity by allowing teams to explore a wider range of solutions and rapidly test emerging ideas. Mentors and instructors also act as key facilitators by offering guidance that strengthens autonomy and reflective practice without limiting student ownership of the innovation process [43]. Equally important is the presence of psychological safety, where students feel valued and supported in proposing novel concepts, challenging assumptions, or learning from iterative failures. When combined with effective project planning, iterative design cycles, and a learning environment that encourages experimentation, these enablers form an integrated ecosystem in which interdisciplinary teams can generate, refine, and implement innovative solutions in realistic, industry oriented contexts.

Despite these strong enablers, interdisciplinary teams in learning factories also encounter significant barriers that can impede innovation and diminish collaborative effectiveness. One of the most prominent challenges is the persistence of disciplinary silos: differences in terminology, cognitive frameworks, and methodological approaches that make it difficult for students to fully understand one another's perspectives. These differences often trigger communication breakdowns, misaligned expectations, and fragmented problem interpretations that slow the progress of innovation. Unequal participation further intensifies this issue, as dominant voices may overshadow important contributions from quieter or less confident members, resulting in decisions that reflect only a portion of the team's collective expertise. Power dynamics rooted in perceived disciplinary hierarchy, differing technical proficiency, or personality imbalances can weaken psychological safety and discourage open dialogue. Institutional constraints such as rigid assessment criteria, limited time for exploration, or lack of flexibility in project structures can restrict the iterative experimentation required for breakthrough ideas. Additionally, inadequate physical or digital collaboration spaces may hinder teamwork by limiting interaction and reducing opportunities for spontaneous idea exchange. Without intentional intervention to mitigate these barriers through inclusive facilitation, equitable role distribution, conflict mediation, structured reflection, and the creation of open, flexible workspaces the full potential of interdisciplinary collaboration cannot be realized. Addressing these limitations is therefore vital to enabling learning factories to function as dynamic

innovation ecosystems where students from diverse fields can meaningfully integrate their strengths, challenge assumptions, and develop high level creative and analytical competencies needed for modern professional environments.

2.5. Conceptual Synthesis

A synthesis of the existing literature reveals a deeply interconnected relationship among interdisciplinary teamwork, the learning factory framework, and creativity driven innovation. Interdisciplinary collaboration operates not merely as a cooperative effort but as a transformative mechanism through which diverse knowledge bases, methodological traditions, and problem solving approaches converge to generate novel ideas and breakthrough solutions. Within this process, the learning factory serves as an enabling ecosystem providing a structured yet flexible environment where theoretical principles intersect with experiential, hands on practice. This synergy creates a dynamic learning model that aligns strongly with the core aspirations of Education 4.0, emphasizing adaptability, creative reasoning, critical thinking, and collaborative competence as essential attributes for navigating complex future challenges. Through the integration of theory and practice, learning factories empower students to transcend disciplinary silos, apply systems thinking, and engage in co creation processes that yield innovative solutions responsive to contemporary industrial and societal demands.

The literature further underscores that such outcomes do not occur automatically but require intentional pedagogical design and robust institutional support. Creativity and innovation flourish when interdisciplinary collaboration is scaffolded by structured facilitation, reflective learning cycles, psychological safety, and open, sustained communication among participants. Effective facilitators act as mediators who guide students through conceptual ambiguities, encourage risk taking, and help teams articulate shared goals despite differing disciplinary perspectives. Conversely, rigid curricular structures, highly compartmentalized academic units, and limited opportunities for cross disciplinary engagement can impede the cultivation of interdisciplinary competencies. These constraints may restrict students exposure to diverse viewpoints and hinder the iterative processes essential for innovation to emerge. Consequently, fostering an innovation oriented academic culture demands not only pedagogical refinement but also broader organizational change within higher education such as promoting flexible learning models, strengthening institutional collaboration, and investing in infrastructure that supports interdisciplinary practice. Building on this theoretical foundation, the present study investigates how interdisciplinary teamwork functions as a catalyst for creativity and innovation within learning factory contexts, offering empirical insights that contribute to both conceptual development and practical advances in modern educational design.

3. RESEARCH METHODOLOGY

3.1. Research Design

This study adopts a qualitative case study approach to explore how interdisciplinary teamwork fosters innovation and creativity within the learning factory framework. The qualitative method was chosen because it allows for an in depth and nuanced understanding of participants' lived experiences, cognitive processes, and collaborative interactions, elements that cannot be fully captured through quantitative measurements. The case study design is particularly suited for examining complex, real world learning environments where teamwork, communication, and iterative problem solving evolve dynamically. Within this study, the learning factory serves as an authentic context that mirrors industrial complexity, enabling researchers to investigate how students from engineering, business, and design backgrounds negotiate meaning, integrate knowledge, respond to disciplinary differences, and engage in creative experimentation. By focusing not only on outcomes but also on the processes through which ideas emerge, evolve, and are refined, the research aims to uncover the underlying mechanisms that shape interdisciplinary collaboration in a practice oriented educational setting.

To build a comprehensive and credible understanding of these collaborative processes, data were collected using multiple qualitative techniques including semi structured interviews, non participant observations, and document analysis. Interviews provided rich reflections on how students navigated interdisciplinary challenges, developed communication strategies, and perceived the impact of teamwork on their creative thinking. Observations captured real time behaviors such as coordination patterns, conflict resolution, leadership distribution, and spontaneous idea generation during design and prototyping sessions. Document analysis further grounded the findings by examining project artifacts, reflective journals, proposals, and prototypes that demonstrated the evolution of student thinking throughout the innovation cycle. The triangulation of these data sources enhanced the study's credibility and allowed for a holistic examination of collaborative creativity within the

learning factory. The overall methodological structure, which is illustrated in Figure 1, ensures alignment between research objectives, participant engagement, and analytical procedures, thereby enabling the study to capture the complexity of interdisciplinary dynamics and offer practical insights for designing more effective innovation oriented learning environments.

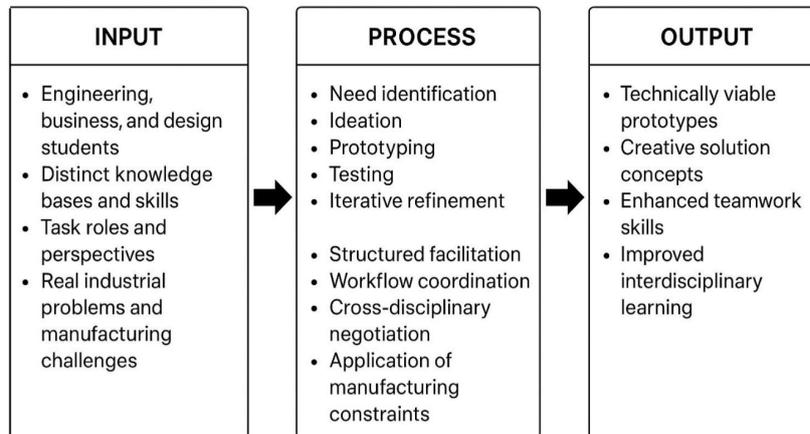


Figure 1. Research Framework

Figure 1 illustrates the conceptual structure of the study, which focuses on fostering innovation and creativity through interdisciplinary teamwork in a Learning Factory (LF) environment. The framework is divided into three key components: Input, Process, and Output. The Input stage involves forming interdisciplinary teams from engineering, business, and design fields within a supportive Learning Factory setting. The Process stage emphasizes collaborative interaction, communication, creative problem-solving, reflection, and facilitator support to guide iterative learning. Finally, the Output stage highlights the expected outcomes, including innovation and creative solutions, enhanced teamwork skills, and improved interdisciplinary learning. Overall, Figure 1 demonstrates how collaborative, interdisciplinary environments contribute to developing innovation and creativity in educational and professional contexts.

3.2. Participants and Setting

The participants in this study consisted of 30 students and 5 instructors drawn from three distinct academic disciplines engineering, business, and industrial design who were actively engaged in interdisciplinary projects within a university-based Learning Factory environment. These participants were selected through purposive sampling to ensure that all individuals possessed prior exposure to collaborative, project based learning contexts, which strengthened the relevance and depth of the data collected. Each interdisciplinary team was required to complete a semester long innovation project addressing authentic industrial or societal challenges proposed by partnering organizations. This structure enabled students to meaningfully apply theoretical knowledge to real world problems while simultaneously experiencing the complexities of cross disciplinary collaboration. The participants brought a diverse mix of technical, creative, and managerial competencies, providing a rich foundation for examining how varying disciplinary perspectives interact throughout the innovation process. Students worked in mixed teams throughout all project phases, including problem identification, design conceptualization, prototyping, and final evaluation, thereby ensuring comprehensive engagement with the Learning Factory workflow.

The Learning Factory setting itself functioned as an essential component of the research environment. It was housed within a semi-industrial laboratory equipped with advanced tools such as 3D printers, simulation and modeling software, rapid prototyping materials, digital design platforms, and collaborative workstations. The physical layout of the space was intentionally designed to support open communication, spontaneous interaction, and flexible team arrangements. This allowed students to transition seamlessly between ideation, design, testing, and revision activities. Instructors within the Learning Factory assumed the role of facilitators rather than traditional lecturers, providing guidance through iterative design cycles, mediating communication challenges, and encouraging reflective dialogue during key project milestones. Their facilitative approach ensured that students maintained autonomy in decision making while receiving structured support when navigating

interdisciplinary complexities. Overall, the Learning Factory offered an authentic, technology rich environment that simulated real industrial conditions, making it highly suitable for exploring the interplay between disciplinary expertise, teamwork dynamics, and the development of innovative and creative project outcomes.

3.3. Data Collection Techniques

Data for this study were collected through three primary qualitative techniques: semi structured interviews, non participant observations, and document analysis. Semi structured interviews served as the central method to capture participants' reflections on how interdisciplinary collaboration contributed to creativity and innovation within the Learning Factory environment. This approach allowed participants to articulate their personal experiences while still providing flexibility for probing questions that explored deeper insights into teamwork dynamics, communication processes, and challenges encountered. Each interview lasted approximately 45–60 minutes and was conducted either face to face or through online videoconferencing tools, depending on participant availability. The interviews were audio recorded with consent and later transcribed verbatim to ensure accuracy in capturing nuanced expressions, emotional undertones, and detailed explanations provided by students and instructors. This interview approach provided rich, thick descriptions that were crucial for understanding the subjective and relational dimensions of interdisciplinary collaboration.

Non participant observations were conducted throughout the semester long project sessions to capture real time interactions between team members. These observations enabled the researchers to document authentic collaborative behaviors, such as communication strategies, task coordination, conflict resolution, and idea generation processes that may not have been fully articulated during interviews. Field notes were taken systematically, including descriptive notes about physical actions, communication patterns, and team workflow, as well as reflective memos that captured the researchers analytical interpretations and contextual insights. This method allowed the study to triangulate self reported data from interviews with behavioral evidence observed in natural settings, providing a more holistic understanding of how interdisciplinary teamwork unfolded over time. Observations also highlighted implicit behaviors such as reliance on certain team members, hesitancy in expressing ideas, or spontaneous moments of creativity that enriched the thematic analysis.

The third method, document analysis, involved reviewing a wide range of student generated materials, including project proposals, design documentation, prototype evaluation reports, presentation slides, and reflective journals submitted at different stages of the project. These documents served as valuable artifacts that demonstrated the evolution of student thinking, decision making rationales, and the integration of disciplinary knowledge into innovative solutions. Document analysis complemented interview and observational data by providing tangible evidence of how teams conceptualized their ideas, structured their workflows, and justified their design choices. It also enabled the researchers to trace the progression of creativity and innovation across the project timeline. The triangulation of interviews, observations, and document analysis significantly enhanced the validity and reliability of the findings by ensuring that emerging themes were supported by multiple sources of data.

Table 1. Research Design Overview

Component	Description
Research Approach	Qualitative Case Study
Research Focus	Exploring how interdisciplinary teamwork fosters innovation and creativity in the learning factory context
Participants	30 students and 5 instructors from engineering, business, and design disciplines
Sampling Technique	Purposive Sampling
Data Collection Methods	Semi-structured Interviews, Observations, Document Analysis
Data Analysis	Thematic Analysis
Duration of Study	One academic semester (16 weeks)
Outcome	Identification of key factors enhancing innovation and creativity through teamwork

Following the detailed explanation of the data collection techniques, Table 1 provides an overview of the research design components and how each element aligns with the methodological framework of this study. The table outlines key components such as the qualitative case study approach, research focus, partici-

pant composition, sampling technique, data collection methods, and analytical strategies. It also includes the duration of the study and the expected outcomes, allowing readers to clearly understand how the research was structured from methodological and procedural perspectives. Table 1 serves as a concise summary that links the conceptual intent of the research with its practical execution, reinforcing the coherence and rigor of the study's design.

3.4. Data Analysis Procedures

The collected qualitative data were analyzed through a rigorous and multilayered thematic analysis approach designed to systematically uncover recurring patterns, conceptual relationships, and deeper meanings embedded within participants' reflections and collaborative experiences. The analytic process commenced with an intensive phase of data immersion, during which researchers repeatedly reviewed interview transcripts, listened to audio recordings, and examined observational notes and supporting documents to obtain a rich and holistic understanding of the overall dataset. This familiarization stage not only built interpretive sensitivity but also allowed the researchers to identify subtle nuances, contextual influences, and emerging points of tension that might otherwise remain hidden. Building on this foundation, the analysis then progressed into a structured coding stage in which descriptive and interpretive codes were assigned to significant statements, observed behaviors, team interactions, and contextual cues related to interdisciplinary collaboration, creativity, and innovation. Rather than treating codes as isolated fragments, the researchers actively compared them across cases and data sources, enabling the identification of convergent interpretations and divergent viewpoints. These codes were subsequently organized into broader conceptual clusters that captured early analytical patterns and revealed underlying links among participants' experiences. Through iterative comparison, refinement, and constant revisiting of the data, these clusters gradually evolved into coherent and analytically sound themes that offered a consolidated representation of the dynamics shaping interdisciplinary teamwork within the Learning Factory environment.

After establishing the preliminary thematic structure, a deeper interpretative analysis was undertaken to explore how each theme corresponded to the study's research questions and theoretical underpinnings. This phase involved examining interrelationships among themes, identifying contextual conditions that facilitated or inhibited collaborative creativity, and evaluating how specific team behaviors contributed to innovation-driven problem solving. Rather than relying solely on surface-level descriptions, the researchers engaged in a critical interpretive process to understand the mechanisms through which interdisciplinary collaboration nurtured idea generation, knowledge integration, and adaptive decision making. To support analytical transparency, qualitative analysis software was used to organize coded segments, track analytical decisions, and enhance the traceability of thematic development. Research rigor was further reinforced through peer debriefing sessions, systematic cross-checking of coded data, and member validation procedures, all of which helped minimize researcher subjectivity and strengthen the credibility of the interpretations. The combined use of these techniques ranging from immersive familiarization to interpretative synthesis resulted in a robust and comprehensive analytical framework. This enabled the researchers to generate theoretically grounded, empirically supported, and richly contextualized insights into the ways interdisciplinary collaboration fosters creativity and innovation within Learning Factory settings.

Table 2. Data Collection Matrix

Research Objective	Data Source	Description of Collected Data	Analytical Focus
To examine how teamwork fosters creativity and innovation	Semi-structured Interviews	Students' and instructors' reflections on collaboration experiences	Identifying factors that stimulate creativity and innovation
To explore interdisciplinary communication dynamics	Non-participant Observations	Notes on team discussions, conflict resolution, and coordination	Understanding communication challenges and strategies
To analyze outcomes of collaborative learning processes	Document Analysis	Project reports, proposals, reflective journals	Linking teamwork processes to creative and innovative outcomes

Table 2 presents a comprehensive overview of the data collection matrix used in this study, illustrating how each data source contributed to addressing the research objectives. Semi structured interviews with students and instructors were employed to explore reflections on collaborative experiences, enabling the identification of factors that foster creativity and innovation within teamwork settings. Non-participant observations provided detailed notes on team discussions, conflict resolution, and coordination processes, offering valuable insights into interdisciplinary communication dynamics and the strategies teams used to navigate challenges. Additionally, document analysis of project reports, proposals, and reflective journals allowed the researchers to examine the outcomes of collaborative learning processes, particularly how teamwork practices translated into creative and innovative outputs. Together, these three sources formed a triangulated evidence base that strengthened the analytical rigor and enriched the overall understanding of collaboration within the Learning Factory context.

3.5. Trustworthiness and Ethical Considerations

Ensuring research trustworthiness and ethical integrity was treated as a foundational component of this study, guiding every stage from design to data analysis. To strengthen credibility, the researchers employed a multilayered strategy that included data triangulation across interviews, observations, and document analysis, allowing the convergence and divergence of findings to be systematically examined. Member validation was conducted not only at the final stage but also iteratively, enabling participants to clarify meanings, correct misinterpretations, and confirm the authenticity of emerging insights. Peer review of coding procedures provided an additional layer of analytic rigor, ensuring that themes were derived through consistent and defensible methodological steps rather than subjective interpretation. Ethical clearance was formally obtained from the relevant institutional review board, and participants received comprehensive information about the study's aim, procedures, rights, and potential risks before providing informed consent. Confidentiality was strictly maintained by anonymizing transcripts, removing identifying contextual markers, and assigning coded identifiers to all participants. All digital files including audio recordings, field notes, and processed transcripts were stored in password-protected, encrypted databases with restricted access limited only to the research team. In addition, participants were fully empowered with the right to withdraw from the study at any point without justification or consequence, reinforcing a research environment built on autonomy, respect, and voluntary engagement.

Beyond procedural ethics, the study also embedded deep ethical considerations into the methodological framework to ensure integrity, fairness, and reflexive awareness throughout the research process. The researchers actively practiced reflexivity by documenting analytic decisions, monitoring personal assumptions, and consistently evaluating how their positionality might influence data interpretation. This reflexive stance played a crucial role in minimizing researcher bias and ensuring that participants' voices remained at the forefront of the analysis. Ethical principles of honesty and accuracy were applied rigorously when interpreting team interactions, contextual dynamics, and personal narratives, ensuring that findings were not overstated or detached from empirical evidence. The study also emphasized respect for participants' autonomy by allowing them to review excerpts of their contributions and provide feedback on how their experiences were represented in the final themes. Transparent documentation of the coding process including memos, analytical notes, and decision trails enhanced dependability and allowed the research to be auditable by external reviewers. By combining methodological transparency, reflexive engagement, and robust ethical safeguards, the study achieved a high degree of trustworthiness, producing interpretations that authentically reflected the complexities of interdisciplinary collaboration while adhering to the highest standards of ethical research practice.

3.6. Summary of Methodological Framework

In summary, this study adopted a qualitative case study design to investigate how interdisciplinary teamwork fosters creativity and innovation within Learning Factory environments. This methodological approach was selected because it allows researchers to capture complex, real world interactions in their authentic context, making it well suited for examining collaborative learning processes that unfold dynamically across multiple disciplines. The integration of semi structured interviews, non participant observations, and document analysis enabled the study to collect diverse forms of qualitative evidence, each contributing unique insights into the collaborative behaviors, communication patterns, and reflective practices of participants. Interviews offered detailed personal narratives regarding teamwork experiences, observations captured spontaneous interactions and problem solving strategies as they occurred, and document analysis provided a record of project evolution, reflective thinking, and learning outcomes. By triangulating these rich data sources, the study constructed a holistic and multi perspective understanding of how interdisciplinary engagement stimulates creative

thinking and innovative approaches to problem solving.

Furthermore, the application of thematic analysis allowed the research to move beyond surface-level descriptions and identify deeper conceptual patterns embedded within participants experiences. Through iterative coding, categorization, and theme development, the analysis illuminated the mechanisms through which interdisciplinary collaboration generates new ideas, integrates diverse knowledge, and encourages adaptive learning. This methodological framework not only produced robust and empirically grounded findings but also demonstrated how qualitative inquiry can reveal the subtle yet powerful dynamics that shape creativity in experiential learning environments. The insights gained from this approach are expected to contribute meaningfully to theoretical discussions on collaborative innovation, particularly within practice based educational contexts such as Learning Factories. Additionally, the methodological rigor applied in this study provides practical implications for educators, curriculum designers, and institutional leaders seeking to cultivate teamwork driven, innovation oriented learning ecosystems. By offering both conceptual clarity and actionable recommendations, the study's methodological synthesis supports ongoing efforts to design educational environments that effectively nurture interdisciplinary creativity and prepare learners for complex, real world challenges.

4. RESULTS AND FINDINGS

4.1. Overview of Data Analysis

The analysis of qualitative data obtained from interviews, observations, and project documentation within the Learning Factory framework revealed a rich set of interconnected themes that illuminate the dynamics of innovation, creativity, and interdisciplinary collaboration. Participants in this study represented diverse academic backgrounds including engineering, design, and business which allowed the research to capture how varied expertise and cognitive approaches converged throughout the project based learning cycle. Over the course of an academic term, teams engaged in iterative design, prototyping, and problem solving activities, creating an authentic environment in which collaborative processes could be observed in depth. Thematic analysis enabled the systematic identification of patterns related to how creativity was generated, negotiated, and sustained across different phases of the learning experience. The findings consistently showed that interdisciplinary teamwork fostered innovation by encouraging students to merge distinct disciplinary perspectives, experiment with alternative solutions, and challenge existing assumptions. Collaborative interactions were enriched when participants drew on their specialized knowledge to propose novel ideas, critique emerging concepts, and co construct shared understandings. At the same time, the analysis highlighted several structural and interpersonal barriers that influenced team performance, including differences in professional vocabulary, contrasting communication styles, and divergent problem solving strategies. These challenges occasionally led to misunderstandings, delays, and conceptual misalignments that required active facilitation, negotiation, and reflective dialogue to resolve. Despite these obstacles, the overall results demonstrate that when supported by appropriate instructional strategies, interdisciplinary collaboration within Learning Factory settings provides a powerful platform for cultivating creativity, enhancing innovation capacity, and preparing students for the complexities of real world professional practice.

4.2. Impact of Interdisciplinary Teamwork on Innovation

Findings indicate that interdisciplinary collaboration exerted a profound and multi layered influence on innovation within project teams, significantly enriching both the development process and the resulting outputs. Students from diverse academic backgrounds contributed not only distinct technical competencies but also unique cognitive styles and problem solving strategies, ultimately enabling the creation of more robust prototypes and creative process solutions. Engineering students frequently ensured the technical feasibility and functional reliability of emerging ideas, while design students brought forward user centered approaches that emphasized usability, experience, and aesthetic value. Meanwhile, business students consistently highlighted issues of market relevance, economic viability, and strategic positioning. This blend of perspectives contributed to a form of cognitive complementarity that strengthened collaborative problem solving, allowing teams to address challenges from multiple angles and avoid disciplinary blind spots. As a result, the innovation process became more holistic, better aligned with real world complexity, and structurally positioned to generate outcomes with practical and commercial significance.

Moreover, innovation was not only reflected in the final products but also embedded in the developmental processes students experienced throughout teamwork. Collaboration required participants to navigate uncertainty, refine communication skills, and adopt adaptive strategies when facing ambiguous or evolving

project requirements. This exposure encouraged students to synthesize diverse knowledge domains, construct shared understanding, and iteratively refine ideas through dialogue and experimentation. The dynamic, iterative nature of interdisciplinary teamwork also cultivated a psychologically safe learning environment, where mistakes were reframed as productive opportunities for exploration, reflection, and creative refinement rather than failures. Such an environment strengthened students' willingness to experiment, challenge assumptions, and pursue unconventional solutions. Consequently, 83% of project participants reported that interdisciplinary collaboration substantially enhanced their capacity to think innovatively, demonstrating measurable improvements in flexibility, originality, and conceptual integration skills essential for thriving within contemporary innovation driven industries.

4.3. Development of Creativity Through Cross-Disciplinary Collaboration

Creativity was found to flourish most effectively in teams where members actively embraced open communication, demonstrated genuine curiosity toward unfamiliar disciplinary viewpoints, and cultivated a deep sense of mutual respect for one another's expertise. Within the experiential structure of the Learning Factory, students were provided with an environment that encouraged rapid prototyping, iterative experimentation, and real time problem validation. These hands on activities exposed learners to a variety of analytical and creative methods, broadening their cognitive flexibility and enhancing their capacity to reframe problems from alternative angles. Interview findings revealed that working with authentic, real world challenges strengthened students motivation to integrate knowledge across fields, leading to solutions that were both innovative and practically relevant. The diversity of disciplinary approaches ranging from engineering precision, design empathy, to business strategic thinking played a key role in triggering creative breakthroughs that would have been less likely to occur in single discipline teams. However, the collaborative process initially presented challenges, as several groups struggled with the absence of shared terminology, differing communication styles, and misaligned expectations regarding workflow and decision making processes.

These early barriers underscored the crucial role played by facilitators, who helped teams establish common goals, align communication norms, and adopt shared frameworks for organizing project tasks. Once these foundational structures were in place, interdisciplinary groups demonstrated significantly higher levels of creative expression. Participants reported feeling more confident and psychologically safe to articulate unconventional or experimental ideas, knowing that their contributions would be valued rather than dismissed. As psychological safety increased, so did the quality of collective ideation, enabling students to propose novel concepts, challenge assumptions, and engage in productive debate without fear of conflict. Over time, the collaborative environment evolved into a culture of learning where mistakes were reframed as growth opportunities and experimentation became a natural part of the teams creative rhythm. Overall, the findings highlight that cross disciplinary creativity is most effectively cultivated when educational settings intentionally foster trust, reciprocal understanding, and structured yet flexible creative processes that allow diverse expertise to interact synergistically.

4.4. Factors Influencing Effective Collaboration

The study identified several interrelated factors that significantly shaped the effectiveness of interdisciplinary teamwork within the Learning Factory environment. Team structure, leadership style, communication quality, and institutional support emerged as the most influential components. Teams that adopted a participative or shared leadership approach where decision making responsibilities were distributed and every members input was valued demonstrated stronger cohesion, higher trust, and more effective problem solving capabilities. This leadership style encouraged open dialogue and empowered members to take ownership of their contributions, ultimately fostering greater innovation. Communication quality further amplified these outcomes; teams that deliberately established communication routines, utilized digital collaboration platforms, and held scheduled feedback or reflection sessions exhibited smoother coordination and fewer misunderstandings. These practices supported transparency, enabled timely adjustments, and created a stable environment in which interdisciplinary ideas could be integrated productively. In contrast, teams that failed to establish communication norms often encountered difficulties, such as unclear expectations, role ambiguity, or delays in task progression.

Institutional support also played a critical role in determining the overall effectiveness of interdisciplinary collaboration. Access to well equipped prototyping facilities, availability of mentors with cross disciplinary expertise, and institutional training on teamwork and collaborative methods provided a foundation for teams to work efficiently and creatively. When these resources were accessible, students felt more confident experimenting with ideas, testing prototypes, and refining solutions without being constrained by technical limita-

tions. Additionally, the introduction of structured project management tools such as shared timelines, milestone tracking, and workflow coordination systems helped teams maintain clarity and organization throughout their projects. These tools mitigated common issues like misaligned expectations or inconsistent work distribution by offering clear guidance on responsibilities and project direction. Conversely, in contexts where institutional support was minimal or guidance was insufficient, teams tended to struggle with coordination, goal alignment, and sustained motivation. Overall, the findings emphasize that effective interdisciplinary collaboration is reinforced through an integrated combination of supportive leadership, strong communication practices, and institutional structures that provide both resources and strategic direction.

4.5. Challenges Encountered During Implementation

The implementation of interdisciplinary collaboration within the Learning Factory environment revealed a series of complex challenges that influenced both group dynamics and project outcomes. Many participants emphasized that disciplinary differences were not merely variations in knowledge but deeply rooted epistemological distinctions that shaped how students approached problem solving. These differences often surfaced in the early stages of collaboration, where team members struggled to reconcile contrasting assumptions, terminologies, and analytical methods. The process of aligning perspectives required extensive negotiation, active listening, and cognitive flexibility, which some students initially found overwhelming. Participants noted that even agreeing on fundamental definitions or conceptual models sometimes required prolonged discussion, demonstrating how disciplinary identity can strongly influence communication patterns. As a result, the early phases of collaboration were characterized by hesitancy, misinterpretation, and the need to continuously revisit shared goals until a functional team rhythm was established.

In addition to intellectual and communicative barriers, participants also reported several structural and operational challenges that significantly affected the continuity of project implementation. Time constraints emerged as one of the most pressing concerns, particularly because students had to manage interdisciplinary project tasks alongside demanding academic schedules within their home departments. These competing responsibilities often created stress and led to uneven participation among group members, complicating coordination and workloads. Furthermore, discrepancies in departmental expectations and assessment standards occasionally generated tension, as students felt compelled to prioritize discipline specific deliverables that did not always align with the interdisciplinary goals of the Learning Factory. Technical issues compounded these difficulties, especially when access to laboratory equipment, digital tools, or specialized facilities was inconsistent across faculties. Such inequalities resulted in project delays, reduced opportunities for experimentation, and in some cases, adjustments to project scope that limited the depth of hands on learning. These structural constraints reveal that interdisciplinary projects require not only student adaptability but also institutional harmonization to ensure resource accessibility and procedural coherence.

Despite these challenges, the study found that many obstacles were gradually overcome through a combination of facilitator support, peer collaboration, and adaptive problem solving strategies. Facilitators played an essential role in mediating conflicts, clarifying expectations, and providing structured guidance that helped teams navigate ambiguities inherent in interdisciplinary work. Their interventions were particularly effective in moments where misunderstandings escalated or when students struggled to articulate discipline specific contributions in ways that others could understand. Peer mentoring also became a powerful mechanism for reducing barriers, as students with higher levels of technical competence or prior project experience assisted others, fostering a more equitable and supportive learning environment. The findings strongly indicate that intentional instructional design such as pre project orientation sessions, team building activities, and explicit communication frameworks can substantially reduce friction and improve collaborative efficiency. These structured support mechanisms not only promote inclusivity but also help balance power dynamics within teams, ensuring that no single discipline dominates and that all participants are empowered to contribute meaningfully. Ultimately, such strategies enhance the overall learning experience and highlight the critical role of facilitation in the success of interdisciplinary educational initiatives.

5. MANAGERIAL IMPLICATIONS

The findings of this study provide important implications for managers and decision makers in higher education institutions that aim to optimize interdisciplinary collaboration within Learning Factory environments. Academic leaders should prioritize the development of structured yet flexible learning ecosystems that support cross disciplinary teamwork by integrating collaborative project management frameworks, shared

assessment rubrics, and unified communication protocols. These structures help reduce confusion between different disciplinary languages and ensure that teams operate under aligned expectations. Faculty members should also be trained to shift from traditional lecturer roles to facilitative leadership, guiding students through iterative design cycles, promoting reflective dialogue, and fostering psychological safety that enables risk taking and creative exploration. Investment in modern prototyping technologies, simulation tools, and digital collaboration platforms is essential, as these resources not only enhance the authenticity of learning activities but also accelerate innovation by allowing students to rapidly test, refine, and validate their ideas. Furthermore, forming partnerships with industry stakeholders can strengthen the relevance and applicability of interdisciplinary projects, ensuring that learning outcomes align with real world skills demanded by innovation driven sectors.

From a managerial perspective, it is also critical to address the barriers identified in this research through intentional organizational policies and infrastructure planning. Institutions should design onboarding programs or interdisciplinary bootcamps that equip students with foundational collaboration skills before engaging in complex projects. This includes training on communication strategies, conflict resolution, and cross disciplinary negotiation to reduce misunderstandings that typically occur in early project stages. Managers should adopt equitable resource allocation models to ensure that all disciplines have balanced access to laboratory equipment, digital tools, and facilitation support. Regular evaluation mechanisms such as reflective journals, team progress reviews, and mentorship feedback loops should be institutionalized to monitor collaboration dynamics and intervene when communication breakdowns or disciplinary dominance emerge. By embedding these support mechanisms into institutional policy, higher education managers can optimize the Learning Factory as a strategic platform for cultivating innovation capabilities, enhancing graduate employability, and reinforcing the institutions role in producing industry ready professionals who excel in creativity, adaptability, and interdisciplinary problem solving.

6. CONCLUSION

The findings of this research demonstrate that interdisciplinary teamwork within the Learning Factory framework plays a crucial role in fostering innovation and creativity among students. Through collaborative learning environments that bring together diverse academic disciplines, participants were able to combine technical, design, and managerial perspectives to generate innovative and practical solutions to real-world challenges. The results show that interdisciplinary learning not only enhances creative problem-solving skills but also cultivates adaptability, reflective thinking, and communication abilities. Moreover, the integration of experiential learning within the Learning Factory setting successfully bridges the gap between theoretical understanding and applied knowledge, preparing students for complex, innovation-driven professional environments.

This study also answers the main research questions by confirming that interdisciplinary collaboration enhances both innovation and creativity when effectively facilitated and supported. The mechanisms contributing to this include open communication, shared leadership, and reflective learning processes. However, the study acknowledges several limitations. The research was conducted within a limited sample size and specific institutional context, which may not fully represent the diversity of interdisciplinary practices in different educational settings. Additionally, while the qualitative approach provided deep insights into participants' experiences, it did not include longitudinal data to measure long-term impacts on innovation capacity or creative development over time.

For future research, it is recommended that studies explore longitudinal and mixed-method designs to better understand the lasting effects of interdisciplinary teamwork on learners' innovation skills and professional growth. Expanding the scope to include multiple universities and diverse disciplines would enrich the generalizability of findings. Future research could also focus on developing and testing structured pedagogical models or digital collaboration tools that further enhance creativity and knowledge integration within Learning Factory environments. By deepening the exploration of interdisciplinary learning, future studies can contribute to designing more robust frameworks that empower students to become innovative thinkers and collaborative problem solvers in the evolving global landscape.

7. DECLARATIONS

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7.2. Author Contributions

Validation was conducted by: NA. Conceptualization was completed by: NF. The methodology was developed by: IA. Formal analysis was performed by: KA. Writing, review, and editing were carried out by: RS. Visualization was completed by: NF. All authors, including: NF, NA, KA, IA, and RS, have reviewed and approved the final version of the manuscript.

7.3. Data Availability Statement

The corresponding author may provide the data from this study upon request.

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The authors state that none of their known conflicting financial interests or personal connections could have had an impact on the work that was published in this publication.

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