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What factors may contribute to the improvement of students' interdisciplinary integration competencies?—a comparative study of various interdisciplinary curriculum patterns

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Which curriculum designs are more effective in improving students' interdisciplinary integration competencies? This question remains a focal point in interdisciplinary education research. However, empirical studies on this topic are relatively scarce. Through empirical analysis, this study compared the interdisciplinary integration competencies of students participating in interdisciplinary curricula at two universities in East Asia using the One-way ANOVA method. Through comparisons of student competence differences with corresponding course programs, the study identifies five variables that may impact students' interdisciplinary abilities: the number of foundational courses of other disciplines, the number of interdisciplinary integration practice courses, participation in off-campus internships in interdisciplinary education programs, frequency of forming student teams from different disciplines in courses, and the implementation of team teaching by instructors from different disciplines. Multivariate regression analysis revealed that changes in the number of interdisciplinary integration practice courses and participation in interdisciplinary off-campus internships at the beginning of the curriculum had a significantly positive influence on students' interdisciplinary abilities, with the latter having a greater impact than the former. The study concludes that this phenomenon exists in two universities with completely different social systems, indicating a high degree of objectivity in these findings. These findings provide valuable insights for research on interdisciplinary curriculum design and talent training patterns.

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Introduction

In the face of rapid technological advancements, an ever-changing market, and global climate change, the demand for product innovation and sustainable development has led to increasingly complex and large-scale industrial projects. The boundaries between workpieces, structures, and processes are diminishing, with growing demands at every level and significantly increased problem complexity. Single disciplines can no longer respond fully to these complex issues independently. Therefore, professionals in business, engineering, and design are required to form interdisciplinary teams to address such complex problems (McDermott et al. 2014). This trend has emerged as a defining feature in the field of consumer goods manufacturing and development. Bill Buxton, former principal researcher at Microsoft Research, emphasized that the development of new products is divided into design, engineering, and sales phases, but these phases are not independent of each other. Instead, design, business, and engineering technologies should be integrated across these three phases (Buxton 2010). Consequently, in the highly competitive market, whether in software or hardware, the demand for interdisciplinary talents in product development is increasing. This has, to some extent, driven the development of an interdisciplinary curriculum.

Interdisciplinary courses offer students the opportunity to engage with multiple disciplines and integrate knowledge across diverse fields. Such courses are widely recognized as a critical means for enhancing students' ability to synthesize disciplinary knowledge, commonly referred to as interdisciplinary competence (Lattuca et al. 2017b; Li and Lin 2018). Consequently, numerous universities worldwide have established various interdisciplinary curriculum programs to foster this capability. For instance, Loughborough University in the UK, through its Loughborough Design School (LDS), and Ulsan National Institute of Science and Technology in South Korea, through its School of Design and Human Engineering (SDHE), both offer foundational courses in design and engineering as well as integrated training courses and internships to students who voluntarily participate in their interdisciplinary program projects. These courses aim to cultivate students' abilities to integrate design and engineering knowledge comprehensively and to address complex real-world problems through multi-course learning within the program. While the two institutions differ in specific course offerings and the duration of internships, LDS additionally recruits students from a broader range of disciplinary backgrounds compared to SDHE (Self et al. 2019). In addition, Delft University of Technology in the Netherlands integrates knowledge and concepts from diverse fields such as system biology and mathematics, digestive systems and thermodynamics, and medicine and technology into a comprehensive curriculum, allowing students to use interdisciplinary learning to tackle complex medical and technological challenges (Klaassen 2018). The Vanderbilt University School of Medicine in the United States offers students the opportunity to engage in clinical internships that emphasize interprofessional and interdisciplinary integration prior to their corresponding foundational courses and integrated training projects (Dahlman et al. 2018). Furthermore, some institutions employ various teaching and learning approaches, including single-subject instruction by individual instructors, team teaching involving multiple educators from diverse disciplines (Pollard et al. 2023), and collaborative learning among students from different disciplines (Brassler and Dettmers 2017). However, in the construction of university curricula, faculty members typically operate according to the norms and conventions of their respective disciplines (Holley 2017). Moreover, the goals and orientations for talent cultivation vary across institutions and academic fields. Consequently, the design of interdisciplinary curricula is inevitably shaped by institutional, disciplinary, and even program-specific differences, resulting in diverse offerings of interdisciplinary course programs. As mentioned in the previous examples, these various interdisciplinary course programs may include foundational courses from other disciplines, integrated training courses, or internships; they may consist of only an integrated training course; or there may be interdisciplinary internship courses followed by other foundational courses and integrated training courses. Additionally, they may employ different teaching and learning methods, such as individual or team-based approaches, each with its own distinct course design. In light of the diverse course designs within these interdisciplinary course programs, this paper will collectively refer to the different combinations of course types—including foundational courses from other disciplines, intedisciplinary integration practice courses, internship, along with the various teaching and learning methods—as "curriculum patterns" (the elements that constitute curriculum patterns will be defined in detail in Section "Elements that constitute curriulum pattern").

Faced with such diverse curricular patterns, some researchers have conducted literature analyses and categorized these patterns using three metaphors: the pearl on the string, the zipper, and the snowflake (Lindvig and Ulriksen 2019). These metaphors respectively represent curricular patterns that are linked by a central curricular thread connecting different disciplines; patterns wherein students themselves are responsible for connecting and integrating disparate disciplinary courses; and patterns organized around a specific societal or scientific problem that serves as the unifying core, integrating various disciplines around this focal issue. However, Lindvig and Ulriksen contend that these patterns seem to offer limited support for students' interdisciplinary metacognition and disciplinary understanding, suggesting there is no inherent linear relationship between the design of interdisciplinary curricula and the development of students' interdisciplinary competencies. In contrast, as previously noted, findings by Lattuca, Li, and colleagues appear to diverge from this view (Lattuca et al. 2017a; Li and Lin 2018). This divergence highlights a salient phenomenon: different interdisciplinary curricular patterns may vary in their effectiveness at fostering students' interdisciplinary competence. On the other hand, existing studies differ significantly in how they define the relevant competencies students acquire through interdisciplinary learning, which poses substantial challenges for evaluating the effectiveness of these curricular patterns. Given the scarcity of empirical studies in this area (Gao et al. 2020; Xu et al. 2022), this study argues that, based on a clear definition of students' interdisciplinary competence, it is highly meaningful to investigate, through empirical research on existing interdisciplinary courses and teaching practices, whether there exists a relatively stable curricular pattern that can positively influence students' development of interdisciplinary competence; and further, to explore which specific courses and pedagogical approaches within these patterns may generally enhance students' interdisciplinary capability.

Interdisciplinary competencies and elements that constitute curriculum pattern

Interdisciplinary competencies. Scholars distinguishing between multidisciplinary and interdisciplinary approaches commonly agree that true interdisciplinarity should focus on the integration of contributions from different disciplines, rather than merely highlighting the individual contributions of each. Klein and Newell (1996) have noted that the integration of disciplines naturally constitutes a hallmark of interdisciplinarity. Building on this, Spelt et al. (2009, 2015) explicitly identified the capacity to integrate disciplinary knowledge as the defining characteristic of interdisciplinary competence, further defining interdisciplinary competence as the ability to achieve such integration.

However, what constitutes the essence of interdisciplinary integration competency, and how should it be defined from various dimensions? To date, there is no consensus in the scientific literature on a unified definition of interdisciplinary integration competency (Danilova 2018), Some researchers or institutions have proposed definitions and elements of general interdisciplinary integration competence applicable to their respective disciplines based on the needs of their disciplines. For instance, Luecht et al. (1990) in the medical field proposed that this ability should include four dimensions: competency and autonomy, perceived need for cooperation, perception of actual cooperation, and understanding of others' values. Among these, "competency and autonomy" refers to recognizing and respecting the active participation of each team member while maintaining an open and inclusive attitude toward diverse perspectives. "Perceived need for cooperation" refers to understanding the functions and roles of various disciplines and being willing to share responsibility. "Perception of actual cooperation" refers to students' ability to engage in multidisciplinary practice, comprehend the team's shared goals, be able to rely on each other, and provide comprehensive care for patients. "Understanding of others' values" means that students must apply the skills of all team members in practice, trust their colleagues, and respect and value the professionalism of each team member. The College of Health Disciplines at the University of British Columbia in Canada categorized it into three abilities: "interpersonal and communication skill", "patient-centered and family-focused care", and "collaborative practice" (Wood et al. 2009). It was noted that "communication skills" ensure smooth collaboration among team members from different disciplines. It is considered a more generalized competency, a prerequisite for effective interdisciplinary teamwork, and a necessary component of interdisciplinary practice across all fields. "collaborative practice" lies in the competence to build interdisciplinary teams, such as through mediation of conflicting interests and conflict resolution, to establish effective partnerships to achieve shared goals. Central to this process is the understanding and respect for the roles and responsibilities of other professions. Additionally, Wood et al. emphasize that this framework should serve as a universal standard for interprofessional competence in health services. Wilhelmsson et al. (2012) identified five aspects of interdisciplinary abilities: "teamwork and group processes, reflection and documentation, communication, shared knowledge or general common knowledge base, and ethics". In the field of engineering education, Lattuca et al. (2013) defined interdisciplinary ability as students' capacity to integrate knowledge and methods from different fields for a comprehensive understanding of problems, encompassing eight dimentions: awareness of disciplinarity, appreciation of disciplinary perspectives, appreciation of non-disciplinary perspectives, recognition of disciplinary limitation, interdisciplinary evaluation, ability to find common ground, reflexivity, and integrative skill. Menken et al. (2016) specifically described such integration ability as the amalgamation of different disciplinary concepts, insights, theories, and methods. Although the definitions and elements of interdisciplinary integration competence proposed by these researchers vary across different domains, several ideas exhibit notable similarities. For instance, Wilhelmsson et al. and Wood et al. identified effective communication and collaboration among team members as central to interdisciplinary integration. Similarly, Wilhelmsson et al. and Lattuca et al. both noted that reflection and introspection are crucial to interdisciplinary work, which can help individuals identify disciplinary limitations and facilitate interdisciplinary industry adjustments. Furthermore, Lattuca et al. and Menken et al. both emphasized that integrating methods and knowledge from various fields is core to Interdisciplinary Integration Abilities. Furthermore, Wilhelmsson et al., Luecht et al., Lattuca et al., and Wood et al. stress the importance of understanding and respecting the values and professional roles of team members, as well as addressing ethical issues and establishing common goals. Chen et al. (2017) synthesized definitions of interdisciplinary competence from Luecht et al. (1990), Wood et al. (2009), Wilhelmsson et al. (2012), as well as from the University of Virginia and several medical education organizations in the United States. Through a thorough analysis and categorization of these definitions, they identified five sub-competencies of interdisciplinary integration: communication and collaboration, reflective self-awareness, integrative practice, understanding and respecting others' values, and ethics alongside the pursuit of shared goals. The conceptualization of these five sub-competencies shows substantial overlap with the eight interdisciplinary dimensions proposed by Lattuca et al. (2013), encompasses Menken et al.'s (2016) interpretation of integration, and is notably more concise and explicit. Furthermore, Chen et al. distinguished these five sub-competencies into two categories: the first category—comprising communication and collaboration, reflective self-awareness, and integrative practice—pertains to general group cooperation and problem-solving skills that are discipline-independent and should be acquired by all students following interdisciplinary coursework; hence, they defined this set as "Common Interdisciplinary Integration Based Core Competencies." The second category—comprising understanding and respecting others' values, as well as ethics and the pursuit of shared goals—features discipline-specific characteristics and requires targeted cultivation within particular disciplines, thus representing specialized interdisciplinary competences that lack generalizability; this category was accordingly defined as "Professional Interdisciplinary Integration Based Core Competencies". Chen et al. (2017) clearly define "Common Interdisciplinary Integration Based Core Competencies" as interdisciplinary integration abilities that are not limited by discipline and are general. This aligns with our research objective of understanding whether students from different disciplines show significant differences in common interdisciplinary integration competency indicators after experiencing various interdisciplinary courses and teaching methods. Accordingly, this study will focus on observing students' general interdisciplinary competencies, namely the "Common Interdisciplinary Integration Based Core Competencies".

Elements that constitute curriculum pattern. As the introduction outlines, this paper defines the various combinations of course types and teaching and learning methods in interdisciplinary education programs—including foundational courses from other disciplines, integrative practice courses, and internships—as a "curriculum pattern". For these elements that constitute the curriculum pattern, after reviewing relevant research literature, we have made the following interpretations and definitions.

Curriculum types. Mansilla and colleagues' research found that 75% of teachers believe a solid disciplinary foundation is crucial for achieving high-quality interdisciplinary work. In the process of interdisciplinary integration, the foundational knowledge of the involved disciplines is an essential step for students. Thus, students must understand the theories, concepts, and methods of the relevant disciplines to make informed decisions and references in their interdisciplinary work (Mansilla et al. 2007; Orillion

2009; Xu et al. 2020). Some researchers argue that students participating in interdisciplinary course programs must adapt to shifting disciplinary boundaries and a wide array of new fields. Obstacles to the cognitive understanding of the disciplines involved in interdisciplinary programs may lead to significant difficulties for students (Baishya 2014). Therefore, when students transition from their own disciplines to others, it is essential for them to grasp the foundational knowledge of these disciplines, including core concepts and methods. Courses that impart this type of knowledge have been defined in the literature. For example, Klein (1990) emphasized that students must have a fundamental understanding of related disciplines when integrating knowledge and methods from different fields. He argued that interdisciplinary courses or projects should include "bridge courses", which are foundational courses that help students cross disciplinary boundaries. Furthermore, the design of such foundational courses should focus on interdisciplinary issues to ensure that students can understand and apply core concepts from other disciplines. Newell et al. (2001) refers to these courses as "supportive courses", asserting that they provide students with the knowledge and skills necessary to integrate related disciplines based on the demands of interdisciplinary projects. Repko et al. (2019) propose that interdisciplinary model requires students to master "disciplinary literacy", which involves understanding related disciplines' fundamental knowledge and methods. This literacy is typically developed through foundational courses, which aim to provide students with the necessary disciplinary background for participating in interdisciplinary integration and application. Additionally, some scholars argue that foundational courses in interdisciplinary education should focus on cultivating students' future interdisciplinary problem-solving abilities, emphasizing the practical application of course content for interdisciplinary integration rather than the in-depth study of a single discipline (Bear and Skorton 2018; Jacobs and Frickel 2009). In summary, whether referred to as "bridge courses" or "supportive courses", these courses should be designed to help students cross disciplinary boundaries and address interdisciplinary problems in the future. They should focus on imparting the core concepts and basic methods of relevant disciplines in interdisciplinary learning, enhancing students' ability to recognize knowledge from diverse disciplines and providing practical content for conducting interdisciplinary integration rather than emphasizing in-depth research of a single discipline. Due to its fundamental role in developing interdisciplinary integration abilities, this type of course is referred to as "Foundational Courses of other disciplines" (FCOD).

On the other hand, if the approach to interdisciplinary courses is similar to the 'the pearl on the string' metaphor described by Lindvig and Ulriksen, where only elements of different disciplines are taught to students, this fails to genuinely showcase the core characteristic of interdisciplinarity — integration. Therefore, Baishya argues that interdisciplinary curricula should closely combine integrative courses, working on a common problem to merge two or more disciplines (Baishya 2014). Drake and others point out that while multidisciplinary curricula might share similar themes or capabilities across different disciplinary fields, each discipline remains distinct and separate; in contrast, interdisciplinary integrative courses are more beneficial in developing skills required for the 21st century (Drake and Reid 2018). Furthermore, subsequent studies suggest that fostering students' interdisciplinary abilities should involve a continuum of multidisciplinary, interdisciplinary, and transdisciplinary integrative courses, emphasizing that the fundamental concept of such courses should be student-centered, focusing on broad concepts and skills applicable to real-world problems (Drake and Reid 2020). Indeed, as analyzed earlier in this study, if students merely have an understanding of other disciplines but are unable to integrate different disciplinary knowledge and perspectives to solve real and complex problems, their interdisciplinary abilities are doubtful. Therefore, the inclusion of interdisciplinary integration courses designed to address complex problems is essential for students to engage in interdisciplinary learning. Accordingly, Problem-Based Learning (PBL) and Capstone courses are commonly integrated into interdisciplinary learning programs. First, Capstone courses are typically offered at the final stage of a student's degree program (Dunlap 2005). These courses require students to think critically and explore issues holistically, connecting their prior learning to other disciplines. While not primarily focused on transmitting new knowledge, Capstone courses emphasize practical training that integrates prior learning. It is considered the pinnacle experience for students to integrate, expand, critically assess, and apply their knowledge (Rowles et al. 2004; Wagenaar 1993). Second, Capstone courses that incorporate PBL can guide students in actively participating in identifying, analyzing, and solving real-world problems. This approach fosters critical thinking, problem-solving skills, and self-directed learning and facilitates the integration and expansion of knowledge across disciplines in the process of solving real-world problems (Dunlap 2005). Furthermore, because PBL requires students to address real, complex problems, it inherently involves the integration of knowledge from multiple disciplines, making it an effective teaching method for interdisciplinary education. Subsequent studies have confirmed that PBL is particularly effective in supporting the development of students' interdisciplinary abilities (Brassler and Dettmers 2017). The combination of PBL and Capstone courses is a powerful tool that provides a platform for students to integrate knowledge and skills from different disciplines and also promotes students' ability to work in a broad context and achieve professional competence, which includes interdisciplinary communication, collaboration and innovation (Cornejo-Aparicio et al. 2019). This explains why such courses are prevalent in many interdisciplinary education programs. In this paper, these interdisciplinary education programs that employ PBL for integrating knowledge in Capstone courses are collectively called "Interdisciplinary Integration Practice Courses" (IIPC).

Concurrently, universities are increasingly required to demonstrate the employability of their graduates, graduates' ability to create socially relevant knowledge, and provide tangible benefits to external communities (Kligyte et al., 2022) ; However, many students report facing challenges of knowledge deficiency after graduation, often extending beyond the scope of their academic disciplines (Keryan et al. 2020). To bridge the gap between educational training and industry demands, and to expose students to real-world, complex issues at an early stage, university internships are considered to play a vital role in students' professional development. Internships not only offer students the opportunity to experience real professional environments but also fulfill their need to acquire essential insights, information, and experiences, thereby helping them meet the entry requirements of their chosen careers (Hoyle and Deschaine 2016). Robinson, Nghia, and Binder, among others, also note that internships provide students with a glimpse into work environments that are consistent with or similar to their professional fields, which often influences their professional and career intentions (Robinson et al. 2016; Nghia and Duyen 2019; Binder et al. 2015). This may be because students have the opportunity to link classroom learning activities with real-world applications and personal experiences, thereby gaining a deeper understanding of professional experiences. This, in turn, makes the transition from university life to the workplace smoother and improves their communication skills (Hoyle and Deschaine, 2016). Additionally, internships can enhance students' learning attitudes and behaviors, promoting their reflective abilities (Behrendt 2017; Nghia and Duyen 2019). Studies by Gilbert, Khalil, and Yiu also draw similar conclusions. They believe that during internships, students' communication skills, problem-solving abilities, teamwork skills, and decision-making abilities receive support and further development (Yiu and Law 2012; Gilbert et al. 2014; Khalil 2015). Some scholars have argued that students' exposure to real-world problems during internships, which require integrating knowledge and methods from multiple disciplines, plays a key role in developing their interdisciplinary communication, multidisciplinary analytical perspectives, and teamwork and collaboration skills (Lattuca et al. 2004). Repko et al. also emphasized that such internships offer students opportunities to collaborate with professionals in solving problems and integrating knowledge from different disciplines training them to analyze complex problems, identify the unique characteristics of various disciplines, apply multiple disciplinary tools and methods, and develop integrated solutions (Repko et al. 2019). The key distinction between this form of internship training, which involves interdisciplinary problem-solving, and the Capstone course utilizing the PBL teaching strategy lies in the authenticity of the working environment in which students are placed. In particular, students work not only with peers from different disciplines on campus competencies but also with professionals from diverse fields, bringing significant practical experience. Their influence on the development of students' interdisciplinary integration competencies may be even more profound. Students gain a more profound understanding of interdisciplinary integration in such an environment. However, other research has found that students often discover they lack the necessary background knowledge or skills during internships, facing challenges in quickly integrating into organizations and transferring tacit knowledge (Bernsteiner and Schlögl 2016). Lynda Holyoak found some extreme cases in a few internship scenarios, which, though not necessarily common, confirm the possibility of their existence. Her research indicates that not every student has equal access to internship opportunities and developmental experiences. In some cases, the transfer of knowledge and experience between interns and their mentors is not always harmonious, resulting in a disconnect between students' development and the knowledge and skills required by specific courses (Holyoak 2013). Despite this, internships remain a necessary part of many educational programs. For instance, the Association to Advance Collegiate Schools of Business in the United States recognizes internships as a means of supporting experiential learning, alongside interdisciplinary learning projects, as activities that support student development. They believe that internships are essential for interdisciplinary learning and work (Dent and Jo White 2020). For the convenience of the subsequent study, we will refer to these internships as "Off-campus Internships in Interdisciplinary Education Programs" (OIIEP).

Teamwork in learning and teaching. As previously mentioned, numerous scholars and organizations agree that students' ability to collaborate in teams is one of the main dimensions of interdisciplinary integration competency (Chen et al. 2017; Wilhelmsson et al., 2012; Xu et al. 2022). Some researchers even consider students' participation in interdisciplinary team collaboration as a crucial characteristic of interdisciplinary curricula. For instance, the study by Mirjam Brassler and others directly excluded courses where students did not engage in interdisciplinary team collaboration or only participated minimally, arguing that such courses are not true interdisciplinary ones (Brassler and Dettmers 2017). Nilsa and colleagues also emphasize that interdisciplinary educational patterns should include interdisciplinary team research to achieve deep integration among students (Bosque-Pérez et al. 2016). Therefore, the importance of teamwork in students' interdisciplinary learning is self-evident. In interdisciplinary education, enabling students to collaboratively learn, share, communicate, and coordinate knowledge and perspectives from different disciplines, and work together to solve problems, should be an essential part of their interdisciplinary learning experience. In fact, defining the interdisciplinary nature of teams composed of students from different disciplines in interdisciplinary education is challenging. Bosque-Pérez suggests that interdisciplinary teams should conform to the "shield-shaped competency model", where team members not only possess deep knowledge in their own disciplines but also have the ability to collaborate with other disciplines to solve complex problems (Bosque-Pérez et al. 2016). Mirjam Brassler and others note that the primary distinction between interdisciplinary teams and multidisciplinary teams lies in the former's requirement for high levels of cooperation and integration among different disciplines, enabling them to make informed decisions and work collaboratively. In contrast, the latter consists of team members who operate independently according to their own disciplinary standards, with cooperation being more parallel and assistive rather than integrative (Brassler and Dettmers 2017). Xu et al.'s research found that even when teachers require the formation of interdisciplinary teams in teaching, and the assignments involve complex problems that necessitate interdisciplinary integration to solve, some teams still operate independently, adhering to their disciplinary standards, with little integration between disciplines (Xu et al. 2022). Therefore, based on the standards set by Bosque-Pérez and Mirjam Brassler, and the findings by Xu et al. it can be inferred that teams composed of students from different disciplines may more easily be identified as multidisciplinary. However, without researchers participating in and observing the tasks within student teams, it is difficult to determine whether these teams truly possess interdisciplinary attributes. In this paper, the research team refers to such student learning teams as "student teams from different disciplines, or simply, student teams".

Compared to student teamwork training and learning, how should the teaching approach in interdisciplinary curricula be carried out? Currently, there is no unified teaching paradigm, but interdisciplinary teaching by a team of teachers is increasingly regarded as the optimal means for students to acquire interdisciplinary knowledge and competencies(Pollard et al. 2023). Buckley defined 'team teaching' as a group of teachers purposefully, regularly, and collaboratively working to assist a group of students in their learning (Buckley 2000). Subsequent research proposed that 'team teaching' involves two or more teachers collaborating in course planning, teaching, or assessment (Carpenter et al. 2007; Crow and Smith 2005; Murata 2002; Tsybulsky and Muchnik-Rozanov 2019). Sandholtz categorized team teaching into three types: teachers loosely sharing responsibilities, team planning with individual instruction, and joint planning, instruction, and assessment of learning experiences (Sandholtz 2000). Earlier literature has called for improving teaching quality through cooperation among teachers (Stewart and Perry 2005), especially interdisciplinary collaboration between language experts and content teachers. However, despite longstanding calls, interdisciplinary team teaching remains relatively rare in practice (Lasagabaster 2018; Li et al. 2019). Dalton's study pointed out that team teaching could bring additional challenges and pressures, making interdisciplinary team teaching uncommon in general education (Dalton 2015). Yet, the benefits of interdisciplinary team teaching are undeniable, as it increases the success rate of teachers in training students to solve problems (DiDonato 2013) and enhances the transfer of interdisciplinary skills in teaching (Zell 2019), thereby promoting student learning (Chen 2020). Chen (2020) also found that teachers' confidence and self-efficacy improved positively after participating in interdisciplinary team teaching. Teachers with high self-efficacy are better at maintaining student engagement and encouraging autonomy (Arslan 2019; Chacón 2005), which positively impacts students' interdisciplinary learning. Certainly, just like student teams, teams of teachers from different disciplines also exhibit various forms of interaction across disciplines. Sandholtz defines three types of team teaching patterns: two or more teachers loosely sharing their responsibilities; team planning but individual instruction; and joint planning, instruction, and evaluation of learning experiences (Sandholtz 2000). Therefore, in teacher teams, teaching based on various forms of disciplinary interaction can be multidisciplinary, cross-disciplinary, or interdisciplinary.

Therefore, in certain courses, instruction may involve multiple teachers from different disciplines, each teaching their respective areas of expertise or a single teacher delivering content from other disciplines following team-based planning, or a team of teachers from various disciplines collaboratively guiding students through learning or training. For the purposes of this study, these approaches are referred to as "sequential multi-teacher instruction", "single teacher instruction" and "concurrent multi-teacher instruction".

As discussed above, integrating the case studies presented in the introduction with the analysis of the constitutive elements of "curricular patterns" in this chapter, it is evident that different curricular patterns comprise varying combinations of elements. This study primarily aims to explore which curricular patterns, or which specific factors within these patterns, may contribute to the enhancement of students' interdisciplinary competence.

Materials and methods

In this study, the research samples, encompassing the relevant elements of the interdisciplinary curriculum pattern, were collected from two East Asian universities. These samples include course materials and student questionnaires for each university's interdisciplinary curriculum program. Students at both universities share Chinese as their native language and similar cultural customs. However, they have grown up under different social systems, resulting in significant differences in their upbringing and educational environments. Since the universities involved in the study preferred not to disclose their names, we have designated them as University-A and University-B for the purpose of differentiation and discussion in this research.

Setting and teaching of interdisciplinary curriculum

Setting of interdisciplinary curriculum

University-A: University-A, established for over 70 years and currently home to nearly 30,000 students. In recent years, to address societal development challenges, meet labor market demands, and enhance students' interdisciplinary capabilities, the university has integrated interdisciplinary curricula into these four majors: Communication Engineering, Digital Media Technology, Business Administration, and Product Design. Considering the diverse needs of faculty and the distinct characteristics of each discipline, the four majors have adopted a collaborative approach to provide mutual faculty support, while individually tailoring their interdisciplinary course projects to meet their specific requirements. Therefore, the interdisciplinary curricula for the four majors differ (see Appendix 1), however, as discussed earlier in this paper, the programs followed similar model principles, including the inclusion of FCOD, IIPC, and OIIEP in some of the programs. The number of each type of course, the teaching format, and whether to invite teachers from other disciplines to teach are determined independently by each major. Additionally, it is important to note that, to maintain diversity in terms of discipline background within student teams, University-A's "IIPC" is not only mandatory for students of the respective major but are also open to students from other majors as elective courses, allowing them to earn equivalent elective credits. The interdisciplinary course programs in Communication Engineering consist of 2 FCODs and 1 OIIEP. Furthermore, their OIIEP, titled "Engineering Internship," requires students to work in engineering design institutes or technology companies in related fields. Students are tasked with integrating knowledge acquired in previous courses within an interdisciplinary task environment, testing their abilities and knowledge, and assisting professionals in solving real-world problems and completing related tasks. (Therefore, based on the course description, this study concludes that the "Engineering Internship" in Communication Engineering exhibits the characteristics of interdisciplinary integration practice courses and should be categorized under both OIIEP and IIPC). The Digital Media Technology program offers 4 FCOD and 2 IIPC: "Interactive Design and Development Training" and "ICT Product Innovation Design and Operation." The Business Administration program provides 4 FCOD and 1 IIPC named "Smart Business Applications Practice." The Product Design program's interdisciplinary curriculum differs slightly, starting with an OIIEP called "Professional Internship," which focuses on extensive interaction with professionals from various disciplines involved in product development to understand related processes and potential issues. This is followed by 1 FCOD and 1 IIPC.

University-B: University-B is a comprehensive private university established with the support of a renowned local manufacturer of 3C (Computers, Communications, Consumer Electronics) products. Because University-B is a corporate-run school, the university and the company are located within the same campus, facilitating convenient communication between the two. Many of the university's faculty members in various majors are former engineers, designers, or managers who previously worked at the company. Consequently, University-B excels in industry-education cooperative teaching. Currently maintaining a student body of around 5,000, its mission is to cultivate applied and interdisciplinary talents in line with industry development needs. Through years of educational exploration, the General Education Center at University-B has integrated courses and faculty from business, engineering, and design fields to cater to diverse majors such as Materials Engineering, Mechanical Engineering, Electrical Engineering, Computer Science and Engineering, Industrial Design, Media Design, Business Management, and Applied Foreign Languages. Aimed at fostering interdisciplinary integration competencies, the center offers a uniform set of interdisciplinary curricula for all students, including FCODs such as Applied Electronic Creation, Business Analysis, Design Fundamentals, and IIPC, such as Capstone Projects, totaling 18 courses. Notably, before 2021, the interdisciplinary curricula included 21 courses, comprising Interdisciplinary Topic 1 and Interdisciplinary Topic 2, as well as an Innovation and Entrepreneurship Course offered in the junior and senior years, which were later removed without explanation by University-B. As these courses are sequentially interconnected, students must commence the series from their freshman year, with the option to withdraw but not to join midway. In addition, the university's Master's programs in Industrial Design also offers interdisciplinary curriculum, including an OIIEP "Factory Internship", a FCOD "Universal Design," and an IIPC "Thematic Design" (see Appendix 1).

Teaching of interdisciplinary courses

University-A: According to the teaching materials from University-A, the FCOD in Communication Engineering, Digital Media Technology, and Business Administration are all taught by a single teacher from the respective discipline, a form referred to in this study as "single teacher instruction". These courses primarily employ a combination of theoretical lectures and project training, aiming to familiarize students with basic terminology, knowledge, and methods from other disciplines. In contrast, the "Introduction to Information Technology Applications" course in the Product Design major is initially taught by a teacher from the field of Information and Communication Engineering, covering foundational knowledge of the discipline. In the latter part of the course, a Product Design teacher joins in to guide students in completing a design project that involves communication technology. Both teachers from different disciplines actively participate in the students' team discussions and presentations. This is the type of "concurrent multi-teacher instruction" named in the paper.

The university's OIIEP, "Engineering Internship" for Communication Engineering and "Professional Internship" for Product Design, both require students to find positions that align with their professional direction. Therefore, students need to go to R&D design positions in 3C product or automobile manufacturing companies that have partnerships with the university, or independently find similar positions in relevant institutions to complete the internship course. Due to the nature of these positions, students will inevitably work with professionals from different disciplines to solve problems encountered in product development, giving students from both majors the opportunity to collaborate with professionals from other disciplines during their internships. However, according to the course descriptions, Product Design students are jointly guided by university faculty and corporate mentors. Each university instructor is responsible for supervising 1-8 students, which includes weekly offline or online reports and discussions about the students' internship progress and issues. The purpose of this course is to help students understand the various problems involved in each stage of the product development process. On the other hand, the Communication Engineering internship is solely guided by corporate mentors, and students are required to integrate their prior knowledge, validate their abilities and knowledge during the internship, and complete assigned tasks with company personnel. Students from both majors are required to submit an internship report at the end of their internship. The job description, performance, attitude, and abilities evaluation sections of the report are filled out by the corporate mentors. Product Design instructors use this information to judge whether the interns have engaged in sufficient interdisciplinary collaboration and assign the final grade for the course. For Communication Engineering, the corporate mentors directly provide the students' grades in the internship report.

The courses "Interactive Design and Development Training" and "ICT Product Innovation Design and Operation" in the Digital Media Technology program, "Smart Business Applications Practice" in Business Administration, and "Product Project Design" in Product Design are all interdisciplinary integrative practical courses. These courses require students to form teams with peers from other majors to complete project training tasks. The distinction lies in the fact that in "Interactive Design and Development Training" and "ICT Product Innovation Design and Operation," the teaching is initially conducted in stages by faculty from the respective disciplines. Subsequently, these courses are led solely by a single teacher from the Digital Media Technology program for project training and practical guidance. So they belong to the "sequential multi-teacher instruction" mentioned in the paper. The "Smart Business Applications Practice" course, on the other hand, is taught and guided entirely by faculty from the same discipline throughout its duration. and belongs to the "single teacher instruction". As for "Product Project Design" in Product Design, the initial phase is taught by design faculty, and as students build teams, faculty from the relevant disciplines are invited to join the design teachers in guiding and assessing the project at its commencement, midpoint, and final stages (for more details, please refer to Appendix 2).

University-B: According to the course information from University-B, the General Education Center at the university has invited faculty from the College of Design, College of Management, and College of Engineering to teach FCOD using a single teacher instruction form. The content of these courses primarily includes introductions or fundamental knowledge in the respective disciplines. The teaching method, similar to that of University-A, combines theoretical lectures with practical training, aiming to familiarize students with basic terminology, knowledge, methods, perspectives, and values from other disciplines. Based on the course tasks, all Capstone courses fall under what this study refers to as " IIPC". These courses are led by teachers from the respective disciplines, and their content focuses on problem-based learning strategies to carry out research practices on small topics. Students are required to integrate the knowledge and methods learned in previous courses to solve the corresponding problems raised in the course. Teaching teams composed of at least three faculty members from the aforementioned three colleges lead the courses, lecturing and guiding students during their allocated time slots, which means multiple instructors teach at different times. Students are required to team up with students from other disciplines to propose solutions to real, complex problems identified during the course, create prototypes, and present their results.

The interdisciplinary teaching in the master's program of Industrial Design at University-B is different. The first-semester "Factory Internship" is similar to the internship course in the Product Design program at University-A. Students are required to complete their internship tasks at design and development positions in the 3C product manufacturing factories owned by the university's founding company. The course is jointly led by a corporate mentor and a faculty instructor from the design department. The faculty instructor can visit the company at any time to check on the students, understand their situation, and provide suggestions. Under the corporate mentor's arrangement, students are required to assist members of different project development teams, complete assigned tasks, establish communication with professionals from different disciplines, and understand the development and production processes of industrial product design. At the end of the internship, under the guidance of the corporate mentor, students are expected to complete a small product design project. Typically, students need to seek help from professionals in different disciplines within the company and discuss their projects with them. The corporate mentor and the faculty member from the design department will ultimately judge the feasibility of the students' design projects and assess their level of interdisciplinary knowledge and integration, and provide a grade. The "Universal Design" course is co-taught by two faculty instructors from the design department and two faculty instructors from a local medical nursing university's nursing department. In the initial phase of the course, teachers from the two different disciplines introduce and explain some fundamental knowledge and methods of their respective fields. In the later phase, during the design and development of medical nursing products, the course adopts a team-teaching approach, with all four teachers jointly guiding the students. The "Special

Topic Design" course is led by the course director, who invites teachers and students from different disciplines to form teaching and student teams, respectively, to complete the course tasks together. Both the teaching and student teams consist of members from various disciplines. The teaching team consistently guides the course with a focus on real-world problems, requiring students to complete a design project. Each session uses a team-teaching approach with multiple teachers instructing simultaneously (see Appendix 2).

In addition, it is also important to obtain information on the participation of students and teachers in interdisciplinary curriculum projects at the two universities and the actual implementation of the curriculum. However, due to various constraints at the time, in the preliminary data collection work, this study could not obtain detailed information on the execution of specific teaching tasks in the curricula at either University-A or University-B. For example, the actual situation of students in internship courses remains unclear. Although almost all students interned in the R&D departments of companies, where they possibly encountered professionals from different disciplines due to the nature of their work, this does not necessarily mean that students worked in genuine interdisciplinary teams and integrated knowledge to solve complex problems. Some companies' design and development departments may only operate in a multidisciplinary rather than interdisciplinary manner. For instance, in certain courses at the two universities, both teachers and students come from teams with diverse disciplinary backgrounds. The effectiveness of these teams in performing their interdisciplinary integration tasks remains uncertain. Consequently, it is challenging to accurately assess whether the implementation of these courses is genuinely interdisciplinary. However, based on the course materials outlining the requirements and teaching strategies of each course, we provisionally classify these courses, as well as the student and faculty teams, as "interdisciplinary". At the same time, this study also decided to first analyze the existing course materials, and then, based on the analysis, conduct targeted interviews with relevant course programs leaders to assess whether the elements are genuinely interdisciplinary and explore their impact on students' interdisciplinary competencies.

Analytical methods. Biggs's (1993) Model of Classroom Learning posits that students' prior knowledge, abilities, preferred learning approaches, values, and expectations, together with teaching context factors—such as curriculum, teaching methods, classroom climate, and assessment—collectively influence students' learning outcomes and performance (Biggs 1993). Empirical studies by Spelt et al. (2009, 2015) confirmed the impact of these factors on students' interdisciplinary competence levels. Additionally, other researchers have identified that students' interdisciplinary learning motivation, prior learning experiences, and cognitive factors may also affect their ability to integrate knowledge across disciplines (Xu et al. 2022). Given the multitude of potential influences on students' interdisciplinary competence, it is practically impossible to comprehensively gather and analyze all relevant data and variables to ascertain their effects. Moreover, as noted in Section "Setting and teaching of interdisciplinary curriculum" regarding the realities of data collection, this constraint evidently limits the possibility of fully exploring all factors influencing students' interdisciplinary integration ability. Nonetheless, in the absence of complete information on all variables, regression analysis can still be applied to determine whether variations in one or several known factors significantly affect a given outcome (Chen and Wang 2010). This approach thus offers educational institutions a feasible way to investigate how curricular design and teaching modalities impact students' interdisciplinary integration competence. Accordingly, this study focuses solely on the curricular arrangements and mandated teaching formats in two universities and their effects on students' interdisciplinary integration abilities.

On the other hand, as stated earlier, our sample data originate from two institutions operating under distinct socio-political systems. These institutions differ markedly in terms of education policy implementation, institutional philosophy, developmental directions, instructional management, and student quality, among other aspects. Such differences may yield substantial variations in teaching and learning experiences between faculties and students, potentially confounding the data analysis. To address this, the study adopts a two-stage approach: first conducting internal analyses within each institution to examine differences in curricular models and teaching methods, followed by a comparative analysis across the two institutions to identify any common patterns. This methodology aims to enhance the objectivity and accuracy of the research findings and, to some extent, address the research questions posed at the conclusion of the Introduction. The specific steps are as follows (See Fig. 1).

Interdisciplinary integration competency measurement tools and samples of students

Interdisciplinary integration competency measurement tools. Interdisciplinary education research has continued to evolve, resulting in the development of various interdisciplinary integration competency measurement tools. Examples include the Interdisciplinary Integration Competency Measurement Scale for engineering students published by Lattuca et al. (2013), mentioned in Section "Interdisciplinary competencies" ; the scale developed by Luecht, Wood, and others for students in medical-related fields (Luecht et al. 1990; Wood et al. 2009); the scale for interdisciplinary work's innovation potential and cooperation released by Claus and Wiese in 2019 (Claus and Wiese 2019); and the General Interdisciplinary Integration-Based Core Competencies scale developed by Chen et al. (2017) for students engaged in interdisciplinary learning. However, the selection of measurement tools must be done with caution. This study aims to measure the interdisciplinary integration competencies of students from various disciplines, so the chosen measurement tool should not be limited to students of a particular discipline but should be general and applicable to a wide range of fields. Moreover, the understanding and expression of the same concept may vary across different cultures, and the content of questionnaire items may lead to cultural bias due to a lack of standards. Hence, directly using translated questionnaires might affect the equivalence of the measurement tools (Chang et al. 1999; Lee and Jung 2006). Based on these principles, considering that the participants are native Chinese speakers belonging to the Sinophone cultural sphere, and that the measurement needs to encompass students from multiple disciplines such as engineering, business management, and design, the selection of the instrument must fulfill two criteria: it should be available in Chinese and capable of assessing general interdisciplinary integration competence across diverse disciplinary backgrounds.

The Chinese-language scale developed by Chen et al. (2017) for measuring students' Common Interdisciplinary Integration Based Core Competencies provides a clear operationalization of general interdisciplinary integration competence applicable to students from various disciplines. This conceptualization was elaborated in Section "Interdisciplinary competencies". According to their definition and empirical validation, the Common Interdisciplinary Integration Based Core Competencies can be operationalized through three sub-competencies: communication and

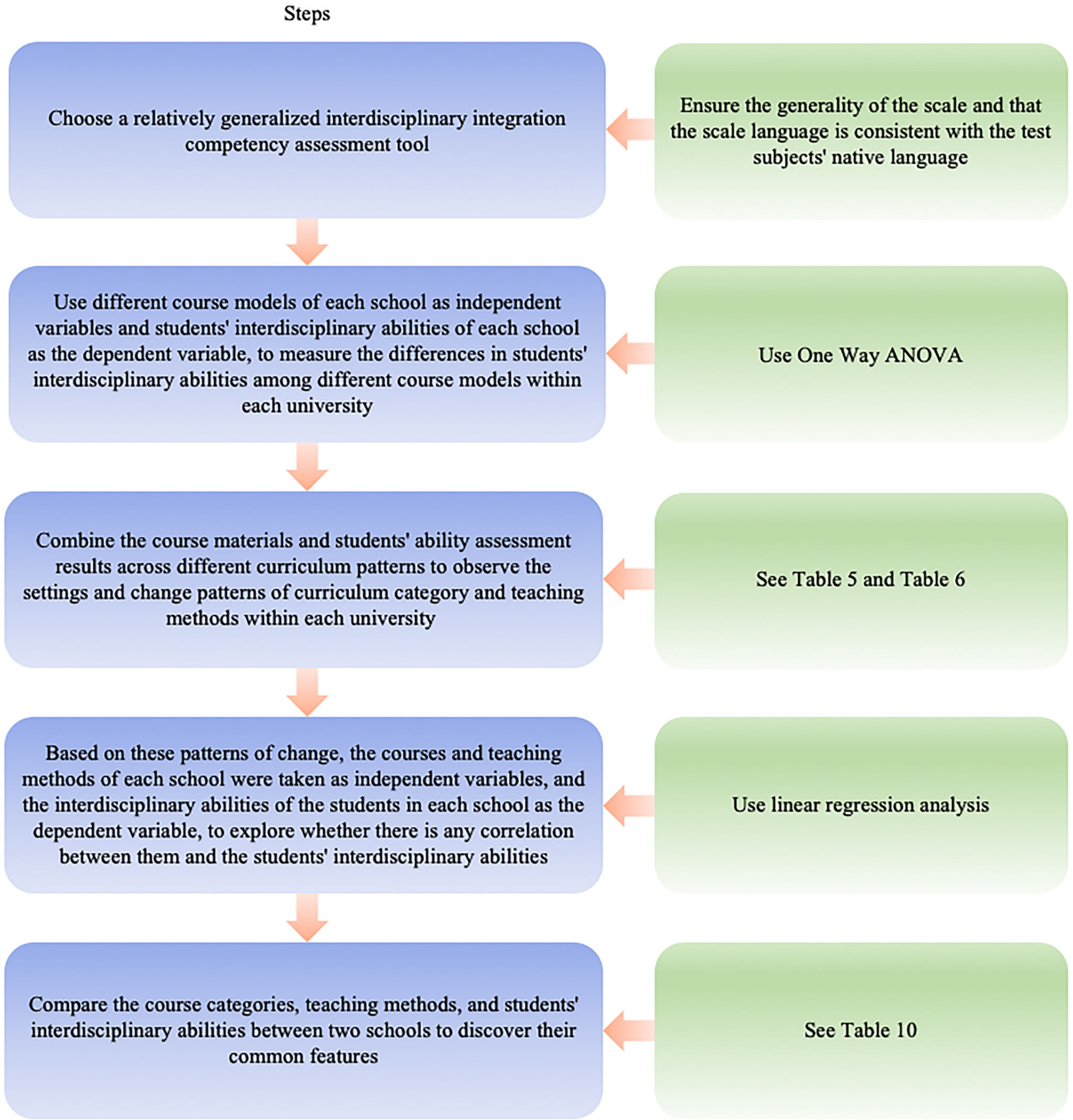

Fig. 1 Steps for analyzing.

collaboration, reflective self-awareness, and integrative practice. Correspondingly, the six items related to communication and collaboration, the five items related to reflective self-awareness, and the five items related to integrative practice are respectively labeled as the three subscale constructs of Interdisplinary Communication, Interdisplinary Reflection, and Interdisplinary Practice, comprising a total of 16 items (see Appendix 3). All items are measured using a five-point Likert's scale, with scores ranging from 1 to 5, representing: "Absolutely not like this," "Not quite like this," "Somewhat like this," "Mostly like this," and "Absolutely like this," respectively.

This scale fully satisfies the criteria set forth in this study for instrument selection. Since its publication in 2017, it has been adopted by multiple universities across East Asia, receiving consistently positive feedback regarding its reliability and validity. Furthermore, to verify the scale's psychometric properties, the research team conducted a pre-test involving 143 students from Universities A and B who had completed or participated in interdisciplinary courses programs. The McDonald's Omega coefficient was 0.874; removing any single item from the 16-item scale resulted in Omega values ranging between 0.857 and 0.870. The item-level ANOVA yielded an F-value of 38.106 with significance below 0.001. Additionally, the Kaiser-Meyer-Olkin (KMO) test value was 0.845. Collectively, these indicators demonstrate high reliability and satisfactory validity, supporting the scale's appropriateness for measurement in this study.

Samples of Students. Given that this study focuses on comparing the effectiveness of different interdisciplinary curriculum patterns, it is essential to ensure that the collected samples fully

Table 1 Measurement variables of One-way ANOVA.

Dependent Variable	Independent Variable	Independent Variable Code	Number of Students Tested	Schools
Common Interdisciplinary Integration Based Core Competencies	Communication Engineering's Interdisciplinary Curriculum Pattern	A-CE	21	University-A
	Digital Media Technology's Interdisciplinary Curriculum Pattern	A-DMT	27	
	Product Design's Interdisciplinary Curriculum Pattern	A-PD	14	
	Business Administration's Interdisciplinary Curriculum Pattern	A-BA	21	
	Undergraduate Foundational Courses of Other Disciplines Pattern	B-UFCOD	27	University-B
	Undergraduate Complete Interdisciplinary Curriculum Pattern	B-UCIC	30	
	Master's in Industrial Design Interdisciplinary Curriculum Pattern	B-MID	20	

Table 2 One-way ANOVA Results for University-A and University-B.

Dependent Variables	Independent Variables	No. of Persons	Mean	SD	FD	*F*	Sig.	Schools
Common Interdisciplinary Integration Based Core Competencies	A-CE	21	57.57	6.683	3, 79	10.111	0.000	University-A
	A-DMT	27	66.00	6.337				
	A-PD	14	68.29	9.482				
	A-BA	21	59.67	6.077				
	B-UFCOD	27	59.41	5.366	2, 74	14.723	0.000	University-B
	B-UCIC	30	63.33	4.270				
	B-MID	20	69.05	8.611				

participated in the interdisciplinary programs of their respective majors or colleges. Based on this principle, from January 2022 to June 2022, this study sampled students from University-A and University-B who had participated in complete interdisciplinary programs, with all sampled students volunteering to participate. To minimize the impact of respondents' potential misunderstandings about the purpose and scale of the assessment, all participating students were informed that the questionnaire results were not linked to their personal academic performance. The researchers introduced the purpose of this study to the questionnaire respondents and explained the scale used in the questionnaire (see Appendix 3). The content of the questionnaire and the meaning of the five rating levels were thoroughly explained to the students. Additionally, the time taken by the students to complete the questionnaire was recorded. Following the team's previous experience using the scale, all questionnaires completed in less than 40 s, as well as those completed in under one minute with identical responses for all items, were excluded. At University-A, samples were collected from senior students of the aforementioned four majors, yielding 83 valid questionnaires. At University-B, based on different interdisciplinary curricula, samples were taken from third-year undergraduate and first-year master's students, resulting in 50 valid questionnaires.

Furthermore, since the interdisciplinary program at University-B allows for mid-curriculum withdrawal, some students chose to exit before the integrated courses in the first semester of their junior year. These students did not participate in the final Capstone integration practice courses. How do the interdisciplinary competencies of students who have completed only part of an interdisciplinary course project compare to those who have completed the entire project? This is a key question that this study seeks to address. Accordingly, this study categorized these students into a separate group named "Undergraduate Foundational Courses of Other Disciplines Pattern" and collected samples from this segment, obtaining 30 valid questionnaires for subsequent comparative research. It should be noted that although students at University-B can voluntarily withdraw from the interdisciplinary program, they are not allowed to drop courses once the semester begins. Hence, the least number of courses completed by students who withdrew was two, and the maximum could be up to eight. However, most students withdrew after the end of the first semester of their freshman year, a few after the second semester, and very few during their sophomore year. Among the 30 valid questionnaires collected, only 3 were from students who withdrew after the second semester of their freshman year, having completed four interdisciplinary foundational courses. The remaining 27 students withdrew after the first semester, having only completed two courses. To ensure consistency in the experimental group, this study ultimately decided to exclude these 3 students, setting the number of participants in this pattern at 27 (see Table 1).

Results

One-way ANOVA comparison of interdisciplinary curriculum patterns of University-A and University-B. The One-way ANOVA results presented in Table 2 indicate that for University-A, the F-value is 10.111 with a significance level below 0.05, and for University-B, the F-value is 14.723 with a significance level below 0.05. This suggests significant differences in student competencies exist among the four interdisciplinary curriculum patterns within University-A and among the three interdisciplinary curriculum patterns within University-B. To further explore specific cases, post-hoc multiple comparisons were necessary. The pre-post-hoc test for homogeneity of variance (see Table 3) showed that the significance for University-A was above 0.05, while for University-B it was below 0.05. This means that the distribution of student ability scores across the three patterns of University-B exhibited heterogeneity of variance, which was not the case for University-A. Therefore, for University-B, Tamhane's method was used for post-hoc testing. The results (see Table 4) indicate that in University-A, students in Product Design (A-PD) and Digital Media Technology (A-DMT) significantly outperformed those in Business Administration (A-BA) and Communication Engineering (A-CE). However, no significant differences were found between Product Design and Digital Media Technology, nor between Business Administration and Communication Engineering. In terms of mean scores, the ranking of student abilities from highest to lowest was: A-PD > A-DMT > A-BA > A-CE. At University-B, students in the Master's in Industrial Design Interdisciplinary Curriculum pattern (B-MID) significantly outperformed those in the other two patterns, and those in the Complete Interdisciplinary Curriculum pattern (B-UCIC) significantly outperformed those in the Foundational Courses of Other Disciplines pattern (B-UFCOD), with the ranking being: B-MID > B-UCIC > B-UFCOD.

Variables involved in the regression analysis of curricula comparison of University-A and University-B. After obtaining the One-way ANOVA comparison results and rankings of the different curricula of University-A and University-B, our research team identified some similarities in their curricula settings and teaching methods, as detailed below:

First, in terms of course offerings, the top-performing models for students at both universities, A-PD and B-MID, each offer only one course in both FCOD and IIPC. Specifically, the number of basic courses is lower than that in other patterns. Moreover, the Off-campus Internships for A-PD and B-MID are scheduled at the beginning of the program, a significant departure from the arrangements of other patterns (see Table 5). Among the two universities ranked second, A-DMT and B-UCIC, the number of basic and integrative practical courses offered is the highest, although they do not include Off-campus Internships. Importantly, there was no significant statistical difference between A-DMT and the highest-ranking A-PD at University-A, whereas a significant difference existed between B-UCIC and B-MID. Furthermore, the lowest-ranking curricula at both universities, A-CE and B-UFCOD, significantly differed from the top two ranking curricula in their respective universities. They both had two foundational courses, which were neither the highest nor the lowest number; in terms of the number of interdisciplinary integrative practical courses, A-CE was the same as the least (A-PD), while B-UFCOD had none. A-CE's interdisciplinary Off-campus Internships course was scheduled at the end of the program, while B-UFCOD did not offer such a course. The ability of students in the A-BA pattern was only slightly higher than that in A-CE, with no significant difference between them. The number of interdisciplinary foundational courses in A-BA was the same as in A-DMT, and the number of interdisciplinary integrative practical courses was the same as in A-PD, A-CE, and B-MID; however, it did not offer an interdisciplinary Off-campus Internships course.

Secondly, regarding the requirements for students to form teams for collaborative training and for teacher teams in course

Table 3 Results of the Test of Homogeneity of Variances for University-A and University-B.

Dependent Variables	Levene Statistic	FD	Sig.	Schools
Common Interdisciplinary Integration Based Core Competencies	1.458	3,79	0.232	University-A
	7.632	2,74	0.001	University-B

Table 4 University-A's Result of the Post Hoc Tests: Multiple Comparisons.

Dependent variables	(I) Independent variables	(J) Independent variables	(I-J) Mean Difference	Std. Error	Sig.	Schools
Common Interdisciplinary Integration Based Core Competencies	A-CE	A-DMT	−8.429	2.03	0.000	University-A
		A-PD	−10.714	2.407	0.000	
		A-BA	−2.095	2.153	0.765	
	A-DMT	A-PD	−2.286	2.298	0.753	
		A-BA	6.333	2.03	0.013	
	A-PD	A-BA	8.619	2.407	0.003	
	B-UFCOD	B-UCIC	−3.926	1.294	0.011	University-B
		B-MID	−9.643	2.185	0.000	
	B-UCIC	B-MID	−5.717	2.077	0.032	

Table 5 Comparison of Course Settings in Different Interdisciplinary Curricula at University-A and University-B.

Schools	Overall Ranking of Competencies	Curriculum Pattern	Number of FCOD	Number of IIPC	Setup of OIIEP		
					At the Beginning	At the End	Not Offer
University-A	1	A-PD	1	1	×		
	2	A-DMT	4	2			×
	3	A-BA	4	1			×
	4	A-CE	2	1		×	
University-B	1	B-MID	1	1	×		
	2	B-UCIC	11	2			×
	3	B-UFCOD	2	0			×

FCOD foundational courses of other disciplines, *IIPC* interdisciplinary integrative practical course, *OIIEP* off-campus internships in interdisciplinary education programs.

Table 6 Comparison of Teacher-Student Team Collaboration in Different Interdisciplinary Curricula at University-A and University-B.

Schools	Overall Ranking of Competencies	Curriculum Pattern	Student Teams	Situation of Team Teaching		
				STI	SMTI	CMTI
University-A	1	A-PD	2			×
	2	A-DMT	1		×	
	3	A-BA	1	×		
	4	A-CE	1	×		
University-B	1	B-MID	3			×
	2	B-UCIC	2		×	
	3	B-UFCOD	2	×		

STI single-teacher instruction, CMTI concurrent multi-teacher instruction, *SMTI* sequential multi-teacher instruction.

Table 7 Variables in Regression Analysis.

Dependent Variable	Independent Variable	Numerical Variable	Categorical Variable	Dummy Variable	Variable Code	Schools
Common Interdisciplinary Integration Based Core Competencies	Number of FCOD	×			X_{A1}	University-A
	Number of IIPC	×			X_{A2}	
	Setup of OIIEP		×	Not Offer (reference variable)		
				At the Beginning	X_{A3}	
				At the End	X_{A4}	
	Frequency of forming interdisciplinary student teams	×			X_{A5}	
	Situation of Interdisciplinary Team Teaching		×	STI (reference variable)		
				SMTI	X_{A6}	
				CMTI	X_{A7}	
	Number of FCOD	×			X_{B1}	University-B
	Number of IIPC	×			X_{B2}	
	Setup of OIIEP		×	Not Offer (reference variable)		
				At the Beginning	X_{B3}	
	Frequency of forming interdisciplinary student teams	×			X_{B4}	
	Situation of Interdisciplinary Team Teaching		×	STI (reference variable)		
				SMTI	X_{B5}	
				CMTI	X_{B6}	

FCOD foundational courses of other disciplines, *IIPC* interdisciplinary integrative practical course, *OIIEP* off-campus internships in interdisciplinary education programs. *STI* single-teacher instruction, *CMTI* concurrent multi-teacher instruction, *SMTI* sequential multi-teacher instruction.

instruction, there are also similarities observed at University-A and University-B (see Table 6). In both universities, the highest-performing curricula, A-PD and B-MID, featured the highest frequency of forming student teams compared to other patterns in their respective university. At the same time, both these patterns employed CMTI in teaching. The second-ranked curricula, A-DMT and B-UCIC, had fewer instances of student team formation compared to the first-ranked A-PD and B-MID and utilized a sequential multi-teacher instruction approach. The A-BA, A-CE, and B-UFCOD curricula had similar frequencies of student team formation as A-DMT and B-UCIC but differed in their teaching approach, utilizing single-discipline teacher instruction only.

Based on the comparison results, within each university, different variables such as “ the number of FCOD, the number of IIPC, Setup of OIIEP, the frequency of team formation among students from different disciplines, and the team teaching situation of teachers from different disciplines” will be considered as independent variables to discuss whether they have a linear relationship with the dependent variable “students’ common interdisciplinary integration competencies.” It’s important to note that “Situation of OIIEP” and “the team teaching situation of teachers from different disciplines” are categorical variables, and they need to be converted into binary dummy variables for linear regression analysis.

In this conversion, the category “not offer” in the variable “situation of OIIEP” and the category “STI” in the variable “the team teaching situation of teachers from different disciplines” are both set as reference variables. All other independent variables, apart from the reference variables, are included in the regression model analysis. Once the results are available, the binary variables in the categorical variables will be compared with the reference

Table 8 Summary of Regression Patterns for University-A and University-B.

Schools	*R*	R^2	Adjusted R^2	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R^2 Change	*F* Change	df1	df2	Sig. *F* Change	
University-A	0.527	0.277	0.250	6.976	0.089	9.736	1	79	0.003	1.654
University-B	0.534	0.285	0.265	6.025	0.058	6.034	1	74	0.016	2.085

Table 9 ANOVA Test Results of Regression Models for University-A and University-B.

Schools		Sum of Squares	df	Mean Square	*F*	Sig.
University-A	Regression	1476.201	3	492.067	10.111	0.000
	Residual	3844.667	79	48.667		
	Total	5320.867	82			
University-B	Regression	1068.852	2	534.426	14.723	0.000
	Residual	2686.135	74	36.299		
	Total	3754.987	76			

Table 10 Regression Coefficients for University-A and University-B.

Schools		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
University-A	(Constant)	53.333	3.328		16.028	0.000		
	X_{A4}	−2.095	2.153	−0.114	−0.973	0.333	0.669	1.494
	X_{A3}	8.619	2.407	0.403	3.581	0.001	0.722	1.386
	X_{A2}	6.333	2.030	0.371	3.120	0.003	0.648	1.542
University-B	(Constant)	59.407	1.159		51.236	0.000		
	X_{B3}	7.680	1.566	0.482	4.903	0.000	0.999	1.001
	X_{B2}	1.963	0.799	0.242	2.456	0.016	0.999	1.001

variables. Additionally, for ease of research, our team has assigned codes to each variable, as detailed in Table 7.

Regression analysis results for University-A and University-B. The results of the multiple linear regression model analysis revealed that three independent variables were included in the regression model for University-A: the number of interdisciplinary integrative practical courses, participation in interdisciplinary Off-campus Internships at the beginning of the curriculum, and participation in interdisciplinary Off-campus Internships at the end of the program. For University-B, two similar independent variables were included in the regression model: the number of interdisciplinary integration practice courses and participation in interdisciplinary Off-campus Internships at the beginning of the program. Apart from these variables, all other independent variables were excluded from the regression model as their inclusion resulted in an F-statistic value greater than 0.1.

In terms of model fit, the R^2 values for University-A and University-B were 0.277 and 0.285, respectively. This indicates that the three independent variables at University-A accounted for 27.7% of the variance in the dependent variable, while the two independent variables at University-B explained 28.5% of the variance. The Durbin-Watson values were 1.654 and 2.085, respectively, both falling within the ideal range of 1.5 to 2.5. This suggests that the residuals in the regression patterns for both universities were independent of each other, meeting the criteria for model estimation as per (Chen and Wang 2010). For more details, see Table 8.

The results of the variance analysis in the regression patterns indicate that the F-tests for both universities were significant, with p-values less than 0.05. This suggests that in the regression patterns of both University-A and University-B, the included independent variables have a significant linear relationship with their respective dependent variables (see Table 9 for details).

Table 10 presents the estimated regression coefficients for University-A and University-B. In terms of the t-values and their corresponding significance levels, in University-A's regression model, both "number of IIPC(X_{A2})" and " OIIEP at the beginning of the program(X_{A3})" showed significance levels below 0.05. This indicates that, after controlling for other variables, both factors still exhibit linear relationships with the dependent variable, "students' common interdisciplinary integration competencies", with regression coefficients of 6.333 and 8.619, respectively. Another variable, "OIIEP at the end of the program(X_{A4})," was also included in the model but showed a significance level of 0.333, indicating it does not have a linear relationship with the dependent variable and has no impact on "students' common interdisciplinary integration competencies". In the regression model for University-B, both "number of IIPC(X_{B2})" and "OIIEP at the beginning of the program(X_{B3})" reached significant levels, with regression coefficients of 1.963 and 7.680, respectively, also suggesting a linear relationship on the dependent variable.

Furthermore, in the regression models of both universities, the standardized regression coefficients Beta (β) for X_{A3} and X_{B3} were 0.403 and 0.482, respectively, both higher than the β values for X_{A2} and X_{B2}, which were 0.371 and 0.242. This will be discussed in more detail in the following section. Table 10 also shows that the Variance Inflation Factor (VIF) values for the variables

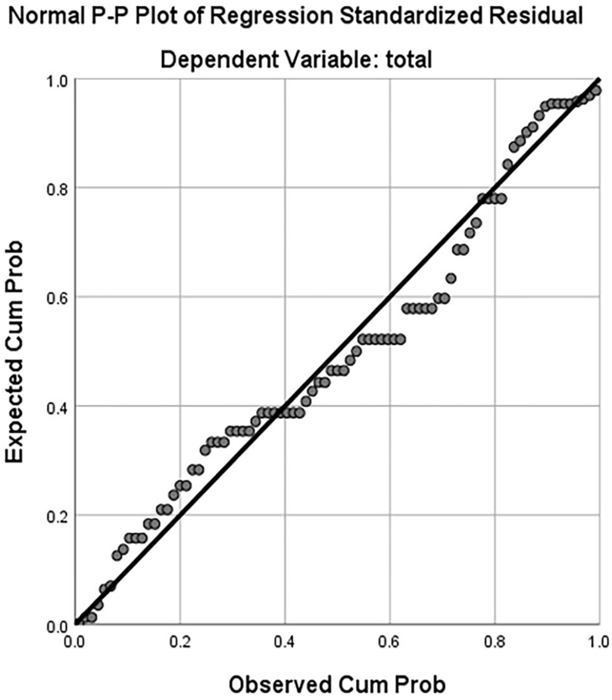

Fig. 2 The P-P plot of the residual distribution in the linear regression analysis of University-A.

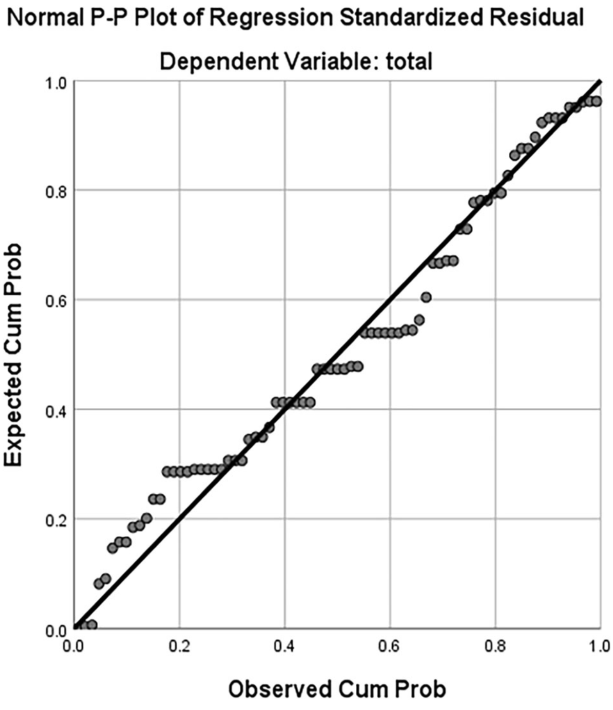

Fig. 3 The P-P plot of the residual distribution in the linear regression analysis of University-B.

included in the regression models of both universities are less than 5, indicating no multicollinearity or low multicollinearity among the variables. Additionally, the residual Probability-Probability (P-P) plots for each model show that the distribution of residuals mostly falls near their respective diagonal lines, indicating a normal distribution and satisfying the assumptions of linear regression models (see Fig. 2 and Fig. 3). Therefore, both regression models are valid. At the same time, the VIF of A and B in the regression models is all less than 5, and the normal distribution of residuals in their respective regression models can further confirm that the confounding variables not included in the regression models have a negligible impact on the analysis results of the regression model.

Building on the foregoing, based on the sample data and analysis conducted in this study, it is observed that at University-A, the variable "participation of OIIEP at the end of the program" within the "OIIEP" variable does not significantly differ from the reference variable "not offer" in impacting the dependent variable "students' common interdisciplinary integration competencies". However, the " participation of OIIEP at the beginning of the program" at both universities, compared to "not offer", shows a significant positive effect on "students' common interdisciplinary integration competencies". Additionally, the variable "Number of IIPC" also has a significant positive impact on the "students' common interdisciplinary integration competencies" at both institutions. The variables "Number of FCOD", "frequency of team formation among students from different disciplines" and "team teaching situation of teachers from different disciplines" did not exhibit a linear relationship with the dependent variable.

Discussion

After multiple linear regression analysis, when identifying the common independent variables that exhibit linear relationships with students' competencies in both institutions, we noted that the constructed regression models for both institutions had R^2 values below 0.3. Typically, this might be interpreted as a low explanatory power of independent variables over the dependent variable. However, Lewis-Beck and Skalaban (1990) have argued that R^2 should be interpreted with great caution and that its meaning must be carefully assessed in the context of the specific research domain and sample characteristics. Hagquist and Stenbeck (1998) studied the importance of R^2 in terms of fit in regression analysis. They argued that the utility of fit measures depends on whether the analysis focuses on interpreting the results of the entire model (model-oriented) or on explaining the impact of specific variables on the outcomes (factor-oriented). They further noted that in some instances, fit has a decisive role; whereas, in other cases, fit is not used as a test statistic but rather as a descriptive measure. In fact, the regression models we constructed are factor-oriented, aiming to investigate whether certain variables exert an effect on the outcome. From the perspective of Hagquist et al., the R^2 in this study functions as a descriptive measure rather than a statistical test statistic, and thus whether it reaches a specific threshold is not the primary concern. Moreover, the significance of the independent variables and the R^2 values in these regression models align with the findings of statistician Ozili (2023), who emphasized that social science research differs from natural science research. If a subset or majority of variables are statistically significant, an R^2 value in the range of 0.1 to 0.5 is acceptable, and there is no rigid rule mandating that R^2 must exceed 0.3. Furthermore, as discussed in Section "Analytical methods" with reference to Biggs, Spelt, Xu and others, factors influencing students' learning performance and outcomes extend beyond the independent variables included in our regression models. Such factors may include students' prior knowledge, abilities, preferred learning styles, values, expectations, interdisciplinary learning motivation and cognition, as well as teaching context variables such as classroom climate and assessment methods. Due to practical constraints, these factors were not sampled nor incorporated into the current models. Consequently, some critics may argue that omitted confounding variables weaken the accuracy of the regression results. In response, we note that (1) our methodological approach involved conducting separate comparisons of curricular models within each institution, which helps mitigate confounding effects arising from differences in schools and student populations; (2) although Wooldridge (2016) warned that omitted variable bias can result in inaccurate regression estimations and that reliance solely on t-test outcomes is insufficient for interpretation, a Variance Inflation Factor (VIF) less than 5—indicating low multicollinearity—can enhance estimation precision; (3) under small sample conditions, the combination of approximately normal residual distribution and VIF < 5 supports the reliability of t-tests and F-tests (Ghasemi and Zahediasl 2012; Vatcheva et al. 2016). Evidently, these conditions are fulfilled in our study in terms of both sample characteristics and analytical results.

Although the R^2 values of the regression models for both institutions are below 0.3, they exceed 0.25, indicating that "participation in off-campus internships at the start of the program" and "number of integrative practice courses" explain approximately 25% to 30% of the variance in students' interdisciplinary integration competence. This level of explanatory power should be regarded as reasonably substantial. Therefore, the current R^2 values of the regression models for both institutions are both acceptable and justifiable. It can be confidently concluded that the independent variables "off-campus internship participation at program outset" and "number of integrative practice courses" each exhibit influential linear relationships with the dependent variable, students' interdisciplinary integration competence, in Universities A and B, respectively. Additionally, statisticians have pointed out that the standardized regression coefficient, β, serves as an indicator of each variable's relative importance, enabling researchers to compare the predictive strength of explanatory variables (Nimon and Oswald 2013; Petchko 2018). As shown in Table 10, the β values for X_{A3} and X_{B3} exceed those for X_{A2} and X_{B2}, respectively. From this, it can be inferred that the positive correlation between the number of integrative practice courses and students' common interdisciplinary integration competencies may not be as pronounced as the impact of participating in OIIEP at the beginning of the program.

However, how do these courses influence students' common interdisciplinary integration competencies? To address this question and gain a more comprehensive understanding of the data analysis results, this study conducted telephone interviews with the course program leaders of the A-PD and B-MID courses (Interviewee 1 and Interviewee 2) to gather insights into the implementation of the "integrative practice courses" and "Off-campus Internships at the beginning of the program." The researcher posed the following questions to Interviewee 1 and Interviewee 2:

a. Could you provide a detailed description of the teaching and learning processes of the "Off-campus Internships at the beginning of the program" and the "integrative practice courses" in the A-PD (or B-MID) curriculum program, along with student participation?
b. Have there been any noticeable changes in students' interdisciplinary learning after completing these courses? If so, what kinds of changes?
c. Do you believe that the "integrative practice courses" and the "Off-campus Internships at the beginning of the program" contribute to enhancing students' interdisciplinary abilities? If so, why?

The following section will discuss the results of the data analysis and the insights gathered during the telephone interviews.

Independent variables included from the regression model

Off-campus internship arrangements. For the Off-campus Internships at University-A and University-B, there are three types: internships at the beginning of the curriculum (referred to as initial internships), internships at the end of the curriculum (referred to as final internships), and no interdisciplinary off-campus internships (referred to as no internships). Among these, A-CE students who only participated in final internships showed no significant difference in interdisciplinary integration competency compared to students in other curriculum patterns without internships. However, students in both University-A and University-B who participated in initial internships demonstrated significant advantages in interdisciplinary integration competencies compared to the other two groups. Additionally, based on the significance indicators, the probability that this phenomenon does not hold for the population, given the sample, is only one in a thousand for University-A and almost zero for University-B. That is, both schools demonstrated the linear law that participation in initial internships inevitably leads to an increase in students' interdisciplinary integration competencies. In this context, can it be said that an initial internship in an interdisciplinary curriculum pattern necessarily improves students' interdisciplinary integration competencies, or is an initial internship necessarily better than a final internship or no internships in terms of improving students' interdisciplinary integration competencies? Obviously, such a conclusion is somewhat simplistic.

Firstly, we note that both schools provide students with internship opportunities aligned with their professional directions. Additionally, the internship courses conducted by A-PD and B-MID involve continuous oversight by on-campus faculty instructors, who keep track of the students' internship experiences. Although the internship courses for A-CE do not have on-campus instructor supervision, they, like A-PD, require companies to provide detailed evaluations of students' work during the internship. A-PD and B-MID instructors then use these evaluations to assess students' performance in the course. Therefore, if students avoid internship arrangements or participate passively, they may not receive the corresponding credits. These measures ensure student participation in internship work. Although this study did not obtain real data on students' internship experiences, and thus cannot confirm whether students truly integrated their previous coursework and received interdisciplinary training during their internships, A-PD, A-CE, and B-MID are all development and design-related programs. The corresponding career positions for these programs inevitably involve tasks requiring collaboration between different disciplines. Given the course requirements for internship positions, students in A-PD, A-CE, and B-MID should have more opportunities to interact with individuals from different disciplinary backgrounds, encounter interdisciplinary collaborative tasks, and understand future work environments compared to students without internship arrangements.

This view was also confirmed by Interviewee 1 and Interviewee 2, the course program leaders. Interviewee 1 emphasized that, at the outset of the curriculum design, they placed significant emphasis on students' understanding of interdisciplinarity. The initial internship course is designed to help students recognize that design innovation and interdisciplinary awareness are inseparable in real work. As a result, students are assigned to relevant partner companies specializing in intelligent cockpit design for automobiles and human-computer interaction design for network technology companies. Typically, students engage in preliminary research for one or two real-work programs. These tasks primarily involve data collection, conducting research interviews, and participating in meetings with professionals from diverse fields, including design, mechanical and electrical engineering, software development, and marketing. Company mentors, who are professionals with extensive experience in interdisciplinary collaboration, guide students in their work. They also receive guidance from their academic mentors on the unknowns they discovered in their respective disciplines. What students encounter most frequently in these work activities are professionals from different disciplines, perspectives on complex issues based on different values, the collision and discussion of multiple points of view, and exploring how designers use the terminology and knowledge of other disciplines to collaborate with other professionals to reach consensus solutions. In fact, after going through all this, the most significant change in students is their newfound understanding and appreciation of interdisciplinarity itself. While they may not yet fully achieve interdisciplinary integration, at least students would know how to communicate effectively with professionals from other disciplines. Another thing is that they can more clearly understand what they lack and which aspects or fields they should improve. Interviewee 2 shares a similar view to Interviewee 1 regarding the course's purpose. They believe that, in today's context, students typically enter the industry only after graduation. Prior to entering the industry, students often have a limited understanding of it. Based on past experience, students often feel confused about what and how to study during the remaining years of their education and how to develop professionally in the future. Initial internships help broaden students' professional horizons from the outset, allowing them to understand the complexity of real problems encountered in the industry while emphasizing the importance of interdisciplinarity. Students are placed in the company established by universities, where they are directly involved in the design and development of household appliances. Both company and academic mentors are professionals with extensive experience in integrating knowledge from various fields in design and development. Moreover, during the development of new products, students frequently interact with electromechanical and structural engineers, in addition to designers. In this context, students participate in discussions on new product development with interdisciplinary teams, which has proven to be highly rewarding for them. Later in the course, students are required to develop their own product design plan under the guidance of the company mentors. The course leader hopes that, by completing this task, students will learn to identify the relevant professionals in the field to consult and discuss with when encountering design-related challenges. Additionally, students are encouraged to establish personal connections with various professionals. Interviewee 2 also emphasized that these personal contacts are informal but may unintentionally provide students with interdisciplinary advice that could benefit their future studies or careers. As a result, students gain greater clarity regarding their professional development and know whom to turn to when they face challenges

Based on the above, A-CE does not assign on-campus instructors to track students' internship progress, which may lead to a lack of supervision in achieving course objectives. There is a risk that the tasks assigned by corporate mentors may not align with course requirements, potentially causing a disconnect between preliminary coursework and later internships. In contrast, A-PD and B-MID have on-campus instructors who continuously monitor students' progress during their internships and provide guidance. The on-campus instructors in these internship courses may complement corporate mentors, or offer alternative support when corporate mentors fall short. O'Higgins' research suggests that instructor support increases the likelihood of students acquiring useful knowledge during internships and positively impacts their future career development (O'Higgins and Pinedo Caro 2021). Furthermore, A-PD and B-MID students are mentored by professionals with established practical experience in interdisciplinary collaboration, which is essential for cultivating students' interdisciplinary abilities. This approach is also consistent with the framework proposed by Lyall et al. (2012). Therefore, we believe that the approach of on-campus instructors tracking student internships and providing support ensures, to some extent, that students encounter and understand interactions between disciplines in real work environments. This foundation helps to build students' awareness of collaboration between different disciplines. This might explain the results of the ANOVA and linear regression analysis: there is no significant difference in abilities between students with final internships and those without internships, while students with initial internship experiences show superior abilities. Additionally, as both interviewees noted, students participating in internships are able to recognize the complexity of real work problems through exposure and hands-on experience, engage in interdisciplinary discussions, and develop a deeper understanding of interdisciplinarity, which allows them to gain new insights and perspectives. Simultaneously, internship participants can clearly identify what they lack in knowledge across various disciplines and are better equipped to seek out relevant experts to solve problems collaboratively. This experience not only shapes students' perceptions and awareness of the interactions and collaborations between different disciplines but also, most likely, aids in developing an interdisciplinary and integrated approach to addressing complex problems. This is likely more beneficial than for those who do not have similar experiences. Several scholars have emphasized the importance of students identifying disciplines with which they may not be familiar and developing a comprehensive understanding of these disciplines in their interdisciplinary learning (Scott, 2022). And the answers given by the two interviewees undoubtedly had a similar effect.

Moreover, based on findings from previous research, we are reasonably confident that such initial internship courses indeed have the potential to enhance students' interdisciplinary integration competence. For instance, from the perspective of Learning Trajectories theory, learning is regarded as a process that follows a particular developmental sequence, describing the general pathways through which students acquire and evolve knowledge within a specific domain. Consequently, curricula or instructional interventions inherently entail a certain order, and educators must understand these trajectories to effectively design curricular systems or models (Clements and Sarama 2004; Simon 1995). Experiential Learning theory further underscores the importance of "learning from experience." Internships represent a prototypical form of experiential learning, enabling students to deepen their understanding and improve relevant skills through iterative cycles of Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation (Kolb 2014). Within an interdisciplinary curriculum pattern, initial internships may be particularly impactful when students' disciplinary knowledge systems are still fluid; early exposure to interdisciplinary work experience can thus initiate this valuable learning cycle, in turn shaping students' subsequent learning trajectories. This view is corroborated by Redfield et al. (2024), who demonstrated that early research experiences significantly influence students' later learning trajectories. Similarly, Petrie-Wyman et al. (2020) observed from motivational and cognitive perspectives that initial internships not only contribute to improved GPA outcomes but also help students establish cognitive frameworks for integrating and applying subsequent classroom knowledge. By engaging with authentic work environments early on, students connect abstract theories to practical application, thereby stimulating intrinsic motivation and clarifying their academic and career pathways (Petrie-Wyman et al. 2020). Additional research findings indicate positive correlations between students' self-efficacy, mental models, and their prior learning and experiential backgrounds (Ramalingam et al. 2004). In interdisciplinary education and pedagogical research, Spelt et al. (2009) likewise contend that students' interdisciplinary thinking and competence are influenced by their educational and social experiences. Early recognition by students of the utility and significance of interactions among disciplines is critically important for the development of interdisciplinary capabilities (Chen et al. 2009; Matthews et al. 2010). Indeed, students are acutely aware of the importance of interdisciplinary learning and its relevance to their short-term goals such as further education or employment (Xu et al. 2022). This aligns with findings by Self et al. (2019), who reported that Korean students, compared to their UK counterparts, express greater concern about the relevance of interdisciplinary learning to their careers—an attitude potentially shaped by East Asian cultural contexts. Keller (1987) also highlighted that such perceived relevance significantly impacts the establishment of learning motivation. From the standpoint of Situated Learning theory, learning does not occur in a vacuum, but is deeply embedded within active, contextual, and cultural frameworks. Learners engage in "legitimate peripheral participation" by participating as novices on the periphery of authentic "Communities of Practice," gradually internalizing the knowledge, behaviors, and values of the community with the expectation of eventually becoming central members (Lave and Wenger 1991). Initial internships effectively transition students from the role of "learners" to that of "legitimate peripheral participants" within interdisciplinary work teams. This transformative shift in identity and context is revolutionary; students observe and emulate experts in real work scenarios, experience the authentic culture of interdisciplinary collaboration, and assimilate its tacit norms. Such experiences profoundly reshape their professional identities and learning motivation, imbuing subsequent learning with purpose and direction.

Accordingly, combining interviews with program coordinators and the aforementioned empirical evidence, we argue that at the onset of interdisciplinary program participation, students' mental models of how interdisciplinary knowledge applies to practice are still under development. From the perspectives of learning trajectories, experiential learning, and situated learning, when instructors monitor and support students while ensuring exposure to interdisciplinary teamwork, initial internships serve as a scaffold that helps students build a real-world-based interdisciplinary cognitive framework. Upon returning to subsequent classroom courses, students can integrate new knowledge into this pre-existing, contextually grounded framework rather than having to construct it anew. Moreover, early immersion in their prospective professional environments clarifies the importance of interdisciplinary learning and its personal relevance, thereby shaping their interdisciplinary learning trajectories. This synthesis of learning trajectories, experiential learning, and situated learning theories thus constitutes a concrete pedagogical practice that establishes "foundational experiences of interdisciplinary learning" for students.

Consequently, this study argues that such internship courses are not only applicable to the design-related majors observed but also generalizable to interdisciplinary curriculum models in other fields or disciplines that require engagement with multiple disciplines for research and development.

The Number of Interdisciplinary integration practical courses. In the studies of University-A and University-B, regression analysis results consistently showed that the number of IIPC, an independent variable, significantly impacts the dependent variable of student ability. In other words, with all other conditions constant, each additional interdisciplinary integration practice course leads to a corresponding improvement in students' interdisciplinary integration competencies. According to the ANOVA analysis of student abilities in both schools, the number of such courses in the A-DMT, A-BA, A-CE, B-UFCOD, and B-UCIC patterns aligns to some extent with these regression findings. Specifically, A-BA, A-CE, and B-UFCOD, which have the fewest interdisciplinary courses, also have lower student ability scores, whereas A-DMT and B-UCIC, with the most courses, have higher scores. However, A-PD and B-MID, the patterns with the highest ability scores, do not have the most such courses. Notably, A-PD's course count is the same as that of A-BA and A-CE, seeming inconsistent with the regression results of both universities. This research infers that since the β values for interdisciplinary internships at the beginning of the curriculum (X_{A3} and X_{B3}) are higher than those for the course count (X_{A2} and X_{B2}), the positive impact of internships on collective interdisciplinary integration competencies likely surpasses that of course numbers. Therefore, even with fewer interdisciplinary courses, students in A-PD and B-MID patterns might still achieve higher ability scores. Additionally, the ANOVA analysis indicates no significant difference in ability scores between students in A-PD and A-DMT, suggesting that the positive impact of internships might compensate for the smaller number of courses, equating the abilities of students in both patterns. Consequently, if students in A-PD and B-MID patterns could participate in more interdisciplinary integrative practical courses, their ability scores could be higher, potentially making A-PD significantly superior to A-DMT. Thus, the ANOVA comparison of student abilities across different patterns does not contradict the respective regression patterns of the two universities.

Additionally, according to Interviewee 1, the integration practice sessions in the A-PD program employed PBL, which required students to synthesize prior knowledge to develop solutions to real interdisciplinary problems. They pointed out that the problems presented to the students were real-world problems in certain fields identified by the students through their prior learning and research in interdisciplinary course programs and subsequently discussed with their mentors. Consequently, each problem is one that the students are personally motivated to solve. The teamwork requirements of the different disciplines from the beginning, as well as the interdisciplinary learning foundation provided to students in the early stages, supported their ability to solve these complex problems. The evolution of the students' problem-solving sketches is evident in the clash of ideas during discussions with peers from other disciplines, followed by the common insights that emerged later on. These sketch processes reflect students' reflection and practice in interdisciplinary learning, contributing to a more holistic understanding of the problem. The B-MID program leader's response in this regard was largely consistent with that of Interviewee 1, potentially due to the shared context of the design discipline. We contend that the interdisciplinary integration practice courses positively influenced the enhancement of students' abilities. For example, the University of Sydney's ICPUs interdisciplinary integration practice courses offer students the opportunity to engage in interdisciplinary programs based on real-world problems. These programs strongly motivate students, many of whom report that the skills and behaviors they acquire align with the competencies needed for employment (Hayes and Cejnar 2020). Other studies have highlighted that such courses enhance student engagement and motivation, leading to improved academic performance. These courses foster a deeper understanding of the topic, allowing students to take ownership of their learning (Drake and Reid 2020). Cuervo et al. concluded that this type of interdisciplinary integrated learning positively impacted students, enabling them to gain a deeper understanding of the topic (Cuervo 2018; DiCamillo and Bailey 2016; Jolley and Ayala 2015). Additionally, the integration and application of knowledge across multiple disciplines enriches students' understanding and enables them to look at things from a more holistic perspective (You 2017). On the other hand, according to the classical theory of Skill Acquisition (Fitts and Posner 1967), students must engage in extensive practice to progress from the novice "cognitive stage" to the proficient "associative stage." Similarly, the fundamental pathway for transforming declarative knowledge into flexible procedural knowledge is through repeated practice (Anderson 1982). The design of multiple integrative practice courses essentially embodies the concept of "mastery learning." Such a design provides students with numerous opportunities for practice, feedback reception, and subsequent refinement. Therefore, this study has grounds to believe that the provision of multiple integrative practice courses offers the necessary training for students to achieve "mastery" of interdisciplinary integration competence (Bloom 1968). These repeated and sustained opportunities for interdisciplinary practice constitute an indispensable element in cultivating complex, higher-order integration abilities. Moreover, from the theoretical perspective of skill acquisition and mastery learning, this form of "sustained integrative practice" is also expected to produce similarly pronounced effects in enhancing students' interdisciplinary integration competence within other disciplinary interdisciplinary curriculum patterns.

Other independent variables excluded from the regression model

Number of FCOD. Since the contribution to the F statistic is not significant when added to the regression model, their P-values are all greater than 0.1, three additional independent variables listed in Table 7—the number of FCOD, the frequency of forming student teams and the situation of team teaching—were not included in the regression analysis model. This indicates that these variables do not impact the dependent variable. This may be attributed to the absence of a linear relationship between the independent and dependent variables; alternatively, multicollinearity among the independent variables may have weakened the individual effects of certain predictors on the dependent variable to the point of statistical non-significance; moreover, the sample size may still be insufficient, thereby obscuring potential significant effects that might otherwise have been detected. (Chen and Wang 2010; Frost 2017, 2019). Due to various reasons, it is difficult to reach a conclusive judgment based solely on the existing sampling data, the school's course introductions, and the interview materials from two curriculum program leaders. However, based on the results of the ANOVA and the data in Tables 5 and 6, we can still make some inferences.

In both universities, the A-BA and B-UCIC patterns had the highest number of FCOD compared to other patterns. However, these two patterns did not rank highest in terms of student ability scores. Notably, A-BA's ability score was significantly lower than that of A-PD, which offered fewer FCOD, and A-DMT, which had an equal number of such courses. A similar situation was observed with the B-UCIC pattern at University-B. Moreover, Spelt et al. have argued that merely adding knowledge from different disciplines only constitutes a multidisciplinary, rather than an interdisciplinary, approach to education (Spelt et al. 2015). This suggests that if FCOD lack integration of knowledge, students will struggle to effectively train and improve their interdisciplinary integration competencies. Although in interviews with the two curriculum program leaders, both acknowledged the teaching of interdisciplinary knowledge integration in their respective foundation courses. However, this study questions whether such explicit teaching of knowledge integration occurs consistently across all foundation courses in these curricula programs. Nevertheless, we also believe that in an interdisciplinary education curriculum, without introductory courses from other disciplines, subsequent integration of knowledge from various disciplines would be impossible. Therefore, this study leans towards the view that the existence of such courses is necessary. Yet, the number of courses offered does not necessarily have an impact on students' overall interdisciplinary integration competencies. This inference is consistent with the concept of threshold concepts proposed by Meyer and Land (2003) and others. They argue that within any discipline, there exist certain core ideas—referred to as "threshold concepts"—which function as conceptual "gateways" or "portals." Once students truly comprehend and cross these thresholds, their perception of the discipline undergoes an irreversible and integrative transformation. In other words, the key to designing interdisciplinary curricula may not lie in the quantity of knowledge points drawn from various disciplines, but rather in assisting students to master the one or two most fundamental threshold concepts within each relevant discipline. Mastery of these threshold concepts effectively provides students with the "keys" to disciplinary integration. Conversely, if students are not supported in overcoming these critical thresholds, no matter how many foundational courses they complete, the educational value remains limited. Therefore, the essential task in curriculum design is to identify and focus on teaching the core threshold concepts necessary for interdisciplinary integration, rather than simply increasing the number of courses.

Frequency of forming interdisciplinary student teams. Regarding team learning of students from different disciplines, this was already mentioned in the second section of this study. Overall, in existing research, this factor is often viewed positively in terms of its impact on students' interdisciplinary abilities. In both universities, the A-PD and B-MID patterns, which had the highest student ability scores, also had the most frequent formation of teams from various fields. However, the second-ranked A-DMT and B-UCIC patterns, significantly superior to A-BA, A-CE, and B-UFCOD, had an equal frequency of students' team formation as these patterns. Considering the regression analysis results and sampling data, this study infers that the team formation frequency of students from different disciplinary might have a relatively minor impact on their interdisciplinary abilities. Although many scholars have noted that interdisciplinary teamwork is an integral part of students' interdisciplinary integration competencies (Chen et al. 2017; Wilhelmsson et al. 2012), but does the frequency of its training necessarily affect students' competencies? We observed that in both schools, students from other disciplines participated in their respective interdisciplinary programs either voluntarily or due to factors such as credit transfer incentives. It is possible that, for students in the A-PD and B-MID programs, although they engaged in two or three rounds of team-based learning, the team members they encountered in each instance were not the same individuals. To verify this, the research team consulted Interviewee 1 and Interviewee 2. Interviewee 1 acknowledged that this situation does occur among their students, but noted that it is not universal across all groups; however, no detailed statistics regarding its prevalence are currently available. Interviewee 2 also indicated that a portion of their students disbanded prior groups and reformed new teams, and some even chose to work independently on course tasks due to difficulties with team formation. Nevertheless, these cases constitute a minority, and Interviewee 2 was unable to provide specific proportions for these occurrences. Xu et al. (2022) found that interdisciplinary student teams sometimes face communication barriers stemming from disciplinary boundaries, a lack of sufficient trust in teammates or instructors, and even emotional outbursts within the team. This aligns closely with Tuckman's (1965) model, which posits that any team formation process involves four distinct stages: Forming, Storming, Norming, and Performing. If students repeatedly form new teams with different members, they have limited opportunity to develop team cohesion and norms (Norming stage), let alone establish a shared interdisciplinary knowledge base or common value system necessary for efficient collaboration during the Performing stage. Consequently, we infer that this dynamic may be one reason why "the number of team formations by students" does not emerge as a significant explanatory variable in the regression models. Yet, due to the lack of more detailed data on student team dynamics within the courses, this inference remains tentative and requires further empirical validation.

Situation of interdisciplinary team teaching. Based on the literature mentioned earlier in this paper, students who have experienced interdisciplinary team teaching with different teachers seem to perform better in interdisciplinary integration competencies. This observation is also reflected in the ANOVA analysis, where the A-PD and B-MID patterns, which involve concurrent teaching by multiple instructors, significantly outperform other patterns. Even the A-DMT and B-UCIC patterns, with sequential teaching by multiple instructors, perform better than the A-BA, A-CE, and B-UFCOD patterns that lack teacher teams. It appears that there is a certain correlation between different disciplinary teacher team teaching and students' interdisciplinary competencies. However, the results of the regression analysis do not fully support this hypothesis. This seemingly paradoxical result appears to reveal the complex synergistic mechanisms underlying instructional interventions. This study posits that this finding does not suggest teaching teams lack importance, but rather that their mode of influence is neither isolated nor direct. On the other hand, from a statistical perspective, this phenomenon may be attributed to interaction effects (Baron and Kenny 1986). Specifically, the true value of the teaching team lies in moderating and amplifying the effects of other instructional activities—such as interdisciplinary integrative practice courses—functioning more as an "amplifier" rather than an independent "engine." At the same time, the high correlation between the teaching team and other curriculum design elements, manifesting as multicollinearity, renders it difficult for the model to isolate their independent contributions (Cohen et al. 2003). Additionally, different disciplinary teacher team teaching has many uncontrollable factors and does not always yield expected results. Havnes (2009) noted that compared to single-teacher instruction, team teaching, despite more collaboration, lacked reflective dialogs and did not show significant differences in teaching practices or classroom strategies. Research by Kevin Francis et al. also points out that within interdisciplinary teaching teams, for teachers accustomed to their own teaching methods and controlling the curriculum, tensions may arise when deciding collectively on the allocation of time to different subjects. Additionally, issues may occur in the division of workload among teachers and in the standards for evaluating students if there is a lack of effective communication and coordination (Francis et al. 2018). These factors can affect the quality of team teaching and consequently the students' interdisciplinary learning outcomes. Therefore, we contend that this finding may provide empirical support for the theory of Holistic Curriculum and the synergy of High-Impact Practices (HIPs) (Kuh 2008). Specifically, teaching teams should not be regarded as isolated variables but rather as key mechanisms for achieving curriculum coherence and integration. By facilitating the fusion and dialog among diverse disciplinary knowledge, teaching teams create conditions that maximize students' benefits from other HIPs, such as internships. Consequently, while the ANOVA results compare the holistic effects of different "instructional design packages," the regression analysis delves deeper within the packages to identify the most immediate driving factors. These conclusions are not contradictory; instead, they collectively portray a more comprehensive picture: successful interdisciplinary education depends on the holistic design that organically integrates various HIPs, and the teaching team likely serves as the pivotal binding agent in this integration. Naturally, the prerequisite for such a role is high-quality collaborative teaching within the interdisciplinary team.

Conclusions

Nowadays, to meet the industry demand for interdisciplinary competencies in product development and design talents, more and more schools are offering interdisciplinary education curricula. However, the industry has yet to reach a consensus on the definition, standards, and evaluation of interdisciplinary competencies, making the effectiveness of these educational curricula programs uncertain. Therefore, it is meaningful to explore whether there is a more generalizable curriculum pattern that can enhance students' interdisciplinary integration competencies across a wider range of disciplines. This study has contributed to the discussion of this issue in terms of research methods and principles of related course design, specifically as follows:

Firstly, prior similar studies have often been limited to single case studies—such as in-depth analyses of a specific successful course project—or simplistic pre-post instructional comparisons. Such approaches make it difficult to disentangle context-specific influences and fail to identify the "key success factors" that transcend particular course models. In contrast, the present study employs a cross-sectional comparative design across multiple course models and seeks commonalities across different institutions. The contributions of this study are twofold: (1) It transcends the limitations of individual case studies by identifying core variables that consistently exert influence across diverse instructional organizational forms. (2) It innovatively combines ANOVA with multiple linear regression analysis. ANOVA is used to compare the macro-level effects of different course models, addressing the question of "which model performs better," while regression analysis attempts to "deconstruct" these models to pinpoint the truly decisive "active ingredients." This approach provides more precise targets for optimizing curriculum design.

Secondly, our study within University-A and University-B in East Asia has found that five factors may influence the development of students' interdisciplinary integration competencies: the number of FCOD, the number of IIPC, the situation of OIIEP, the frequency of forming student teams and the situation of team teaching. According to the regression analysis results, there is a significant positive correlation between students' interdisciplinary integration competencies and both the implementation of initial internships and the number of interdisciplinary integration practice courses. Additionally, a comparison of β values shows that the impact of initial internships is greater than that of increasing the number of interdisciplinary integration practice courses. Based on these results, we propose that the findings related to the two explanatory variables—"initial internship" and "number of IIPC"—may reveal a potentially universal core principle for designing interdisciplinary curricula in product development and other applied fields. Specifically, this principle can be framed as a course design pattern combining "foundational experiences of interdisciplinary learning" with "sustained integrative practice." This framework accounts for why the A-PD and B-MID patterns proved most successful across the two institutions, and why the isolated intensification of a single factor was less effective in alternative models. It underscores the importance of both temporality (establishing foundational knowledge prior to integration) and systematization (both components are indispensable). For all educational programs aimed at cultivating students' interdisciplinary integrative capacities—particularly in fields such as product development, engineering design, and business innovation, where diverse knowledge systems must be synthesized into a tangible or intangible "product"—this framework offers broad applicability and valuable guidance.

However, due to various reasons, the study is limited to data sampled from student questionnaires, some course introduction materials provided by universities, and interview data from individual course program leaders. This means that our findings cannot be compared or verified against the actual experiences and perspectives of those involved. Consequently, this study lacks a deeper discussion of the three variables excluded from the regression model, making it difficult to obtain an accurate conclusion on whether they significantly impact students' interdisciplinary competencies. Moreover, the data collection for this study was limited to University-A and University-B in East Asia. We cannot definitively say whether the findings would remain consistent when including interdisciplinary curricula from other schools. However, we believe that the research approach and steps we proposed can yield more objective conclusions in exploring the elements of interdisciplinary curriculum design. Additionally, to meet industry demands for interdisciplinary competencies in product development and design talent, our data collection focused on highly representative disciplines. As mentioned in Section "Teaching of interdisciplinary courses", the nature of the disciplines in B-MID, A-CE, and A-PD implies that their corresponding internship positions are likely to involve environments where different disciplines interact. These internships are mainly provided by the schools' own enterprises or partner companies. For other disciplines and schools that do not share these characteristics or conditions, it is currently unknown whether initial internships would still enhance students' interdisciplinary competencies. Therefore, from a broader disciplinary perspective, the initiation of interdisciplinary education programs may hinge less on the mere provision of initial internships and more on the pursuit of "foundational experiences of interdisciplinary learning" that build relevant cognitive frameworks, stimulate sufficient motivation, and shape subsequent learning trajectories. Moreover, particularly for applied disciplines, this study advocates for an interdisciplinary curriculum composed of multiple courses rather than isolated single interdisciplinary courses as offered by some institutions. Such a curricular design better ensures the realization of "sustained integrative practice" and is more conducive to enhancing students' interdisciplinary competencies. Additionally, the current study's student sample does not include students from disciplines in the social sciences or similar fields. Whether the curriculum design principles proposed herein equally apply within these domains remains to be empirically validated. Furthermore, this study primarily relies on cross-sectional data, which limits the ability to establish rigorous causal inferences. Future research should consider adopting longitudinal tracking designs to monitor the developmental trajectories of the same student cohorts, thereby enabling more precise evaluation of the long-term effects of various instructional interventions. Complementarily, richer qualitative methodologies—such as content analysis of students' learning journals—could be incorporated to more finely elucidate the specific cognitive and affective processes through which "foundational experiences" influence students.

Despite these limitations, this study's innovative comparative research approach and the construction of the "foundational experience + sustained integrative practice" theoretical framework may offer valuable insights and practical guidance for the field of interdisciplinary curriculum design. We look forward to future research that validates, refines, and extends this principled framework within broader contexts.

Additional information. It should be noted that some of the text, data analysis, and results presented in this article originate from the doctoral dissertation of Dr. Cong Xu, supervised by Professor Chih-Fu Wu. Since this dissertation is part of an ongoing educational research project led by Professor Chih-Fu Wu, the full thesis cannot be publicly disclosed at this time and will remain unpublished until September 2026. However, the text, data analysis, and results included in this article have received publication permission from Professor Chih-Fu Wu, his affiliated institution, and the project administration, making them suitable for publication. This statement is intended to ensure transparency.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to their association with an ongoing government research project, which requires permission from the project's responsible party, its affiliated institution, and managing authorities for data sharing, particularly for raw data, prior to project completion. However, these datasets are available from the corresponding author upon reasonable request.

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Author contributions
This research was conceived and implemented by Cong Xu, who was responsible for a range of tasks, including conducting the literature review, developing the experimental methods, collecting, compiling, and organizing data from the two universities,

performing data analysis, writing the paper, and preparing the tables and figures. Professor Chih-Fu Wu provided valuable guidance and suggestions regarding the research conception.

Competing Interests

The authors declare no competing interests.

Ethical approval

This research has been approved by the Ethics Committee of Behavioral and Social Science Research of Taiwan National University. The license number is: 202105ES161, and the time of acquisition is: July 07, 2021. The scope of the license is applicable to the relevant research of the course involving students' interdisciplinary ability. All data collection and management in the study are based on informed consent, and all respondents are anonymized in accordance with the principles of the 1964 Helsinki Declaration, which is unlikely to have any adverse academic, professional and personal or financial impact on the respondents or test subjects.

Informed consent

Prior to data collection, all research participants were provided with an informed consent form detailing the use of data (including for publication) and potential risks associated with the study. These forms were distributed to participants between January and June 2022, and each participant engaged in relevant research tests or interviews only after providing signed consent. Following data collection, all participants' personal information was anonymized to safeguard their privacy and confidentiality. These procedures ensured that participants' rights and welfare were protected throughout the research process, in compliance with established ethical guidelines for human subjects research.

Additional information

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