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Unveiling interdisciplinary horizons: students' experiences in a first-year calculus course

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In the realm of higher education, the pursuit of interdisciplinarity aims to foster the exchange and integration of fragmented knowledge, yielding transformative outcomes. Employing a phenomenological method, this study delves into the interdisciplinary experience of twelve students from a first-year undergraduate calculus class. Through the analysis of written questionnaires, focus group sessions, and supplementary qualitative data, a comprehensive understanding of students' interdisciplinary encounters is unveiled and organized into three main categories: what students think about interdisciplinarity, how they act when being involved in integrations and what external factors are involved in shaping their experience. This paper presents emergent experiential themes, shedding light on both individual and collective experiences, as students navigate and enrich their calculus learning through interdisciplinary connections.

KEYWORDS

interdisciplinary education, students' perspectives, phenomenological analysis, interdisciplinary experience, calculus, engineering students, higher education, educational innovation

1 Introduction

Interdisciplinary educational perspectives veil knowledge that once was fragmented and atomized within disciplinary and subdisciplinary units. However, these perspectives aim to integrate and transcend their own boundaries. The holistic attributes of interdisciplinary education enhance students' learning experiences and inspire innovative educational strategies (Broggy et al., 2017). As the world grapples with increasing complexities and recognizes the necessity of addressing intricate issues (Davies et al., 2010), the importance of interdisciplinary approaches becomes evident. This realization acknowledges the need to "productively and potently address problems defined by interdependencies across systems" (Tarrant and Thiele, 2017, p. 356), driving the search for linkages beyond disciplinary borders and transversal skills (Carter et al., 2021).

Interdisciplinarity is often referred to as a pedagogical process that identifies common learning and concepts across multiple subjects to address a central theme. It aims to unravel how subjects relate to each other and the overarching theme (Broggy et al., 2017, p. 81). Moreover, it aligns with epistemological definitions that emphasize the integration of "information, methodologies, techniques, skill sets, or theoretical perspectives from two or more disciplines" (Tarrant and Thiele, 2017, p. 355). These notions underscore the significance of cultivating competences for interdisciplinarity, including synthesizing knowledge, fostering complex critical thinking skills, nurturing effective communication abilities, and adopting attitudes conducive to exchanging and transcending disciplinary knowledge in pursuit of integration (Parker, 2010; Madina et al., 2023). These aptitudes are widely regarded as beneficial learning outcomes of interdisciplinary higher education (Spelt et al., 2009, p. 366).

Particularly, interdisciplinary education in mathematics has emerged as a focal research area within mathematics education, particularly concerning teaching and learning phenomena within the STEM education agenda (Williams et al., 2016). However, a notable challenge exists: a "lack of clarity about what mathematics-science integration actually looks like in practice" (Broggy et al., 2017, p. 85), particularly in instructional scenarios where mathematics is not the primary source of disciplinary integration, but rather is perceived as a tool "in the service of science learning." This gap highlights the need for empirical evidence to substantiate learning gains resulting from integration approaches and to comprehend the daily classroom experiences associated with them.

Empirical studies addressing the interdisciplinary education of mathematics focus on teachers' experiences. For instance, they explore the implementation of such approaches in elementary and middle school STEM programs, emphasizing the connections between mathematics and technology (Jehlička and Rejsek, 2018). Similarly, research delves into the experiences of high school vocational teachers engaged in interdisciplinary team-teaching (Kodkanon et al., 2018) and the challenges faced by high school teachers in making curricular trade-offs (Weinberg and McMeeking, 2017). Furthermore, studies investigate teachers' perceptions of STEM pedagogy in higher education (El-Deghaidy et al., 2017; Vink et al., 2017; Dare et al., 2018; Carter et al., 2021), examine the effects of collaborative interdisciplinary modules on students' behavior, attitudes, and motivation (Kelly et al., 2020), and identify systematic and practical concerns in middle schools (Samson, 2014) as well as higher education institutions (Klaassen, 2018; Hart, 2019; Pascale et al., 2021). These studies collectively underscore that interdisciplinary education introduces substantial challenges, not solely concerning teaching and learning dynamics, but also encompassing institutional structures and students' perceptions and appreciation of interdisciplinarity. It is important to note that multidisciplinarity, interdisciplinarity, and transdisciplinarity are all integrative educational approaches and are part of curriculum integration (Beane, 1997; Fraser, 2013), nevertheless their differences rely on the mesh level of connections, focuses, aims, learning outcomes and cooperations.

Epistemological and pedagogical concerns, particularly within higher education contexts, draw attention to issues such as paradigmatic incompatibilities, language barriers, the dominance of ideas, and the need for a deeper understanding of content (Davies et al., 2010). A sufficient grasp of disciplinary knowledge is deemed essential to help students surmount these challenges, enabling them to recognize the necessity for gradual development of interdisciplinary skills and to identify appropriate scenarios for applying interdisciplinary perspectives:

> Within interdisciplinary classrooms often students are presented with contrary disciplinary perspectives that may confuse or frustrate them and unless they have developed a clear understanding of the knowledge and conceptions of the nature of interdisciplinary teaching they will be unable to make sense of the information. (Broggy et al., 2017, p. 82).

Once again, the pivotal concern "of how best to incorporate it (interdisciplinarity) into students' learning experiences is a key consideration in a changing global context" (Davies et al., 2010, p. 19) comes to the forefront. Nonetheless, the experiences and challenges encountered by students within interdisciplinary learning processes remain understudied and insufficiently understood.

Several authors have explored the student experience within pedagogical projects focused on integrating knowledge from various disciplines (Jennett et al., 2017; Self and Baek, 2017; Hall et al., 2018; Munge et al., 2018; Hero and Lindfors, 2019; Power and Handley, 2019). For example, Hall et al. (2018) present findings from a questionnaire surveying the experiences and perceptions of undergraduate students from different higher education institutions that shared exposure to multidisciplinary modules within geography programs. Similarly, Hero and Lindfors (2019) employed a phenomenographic approach to explore how undergraduate students engage with learning in multidisciplinary teams. Jennett et al. (2017) examined the experiences of students participating in a science gamer lab summer school, where interdisciplinary teamwork was an integral component. Additionally, Munge et al. (2018) conducted a literature review on outdoor fieldwork as an experiential learning method in higher education, focusing on the multidisciplinary aspects of fieldwork in various fields. Power and Handley (2019) surveyed the obstacles faced by higher education institutions when integrating interdisciplinarity into student learning experiences, along with identifying key facilitators and potential solutions to enhance the successful integration of interdisciplinary collaboration into the student learning journey.

This background underscores the relevance of employing qualitative inquiry methods to unravel the experiential essence and significance of interdisciplinarity from the student perspective. This paper presents an analysis based on Moustakas (1994) phenomenological method, aimed at uncovering the interdisciplinary experience of twelve first-year undergraduate students enrolled in a calculus course. Through questionnaires, focus group interactions, and reflective journaling, the study seeks to address the following question: How do these students perceive and navigate the presence of interdisciplinarity within a first-year mathematics class?

2 Methodology

In this section, we present the research designed followed by the authors reflection as this project advanced as well as her final reflection looking back. Followed by the participants, data collection, and data analysis.

2.1 Research design

The inherent beauty of the phenomenology philosophy and their derived methods lies in its meticulous capacity to distill and comprehend the intricate diversity of heterogeneous experiences surrounding a phenomenon, ultimately reaching its most refined descriptive and interpretative state. This approach entails a profoundly reflective research process that facilitates a comprehensive understanding of individual experiences in harmony with the broader array of collective experiences. Thus, the essence of participants' interdisciplinary encounters is unveiled in a holistic and untainted manner, offering substantial evidence of interdisciplinary practices in the teaching of integrated college calculus knowledge.

Inspired by the methodological framework proposed by Dare et al. (2018) for comprehending teachers' experiences in implementing interdisciplinary curricular units, this study uses a case study approach for data collection and a phenomenology framework to analyze the data. The selection of a case study methodology stems from its capacity to enhance the descriptions and interpretations of participants' experiences, yielding a diverse range of evidence to construct a 'deep description and analysis of a case' (Creswell and Creswell, 2018, p. 104), which, in the context of this study, pertains to the delineation of the essence of the phenomenon of interest.

Likewise, the philosophy of phenomenology has been adopted to delve into the 'essence or basic structure of the experience' (Merriam, 1998, p. 16), specifically interdisciplinarity. This entails employing firsthand data that captures participants' experiences within a specific context – the setting being a first-year college calculus class. This approach engages in a fundamentally philosophical exploration to perceive interdisciplinarity as a phenomenon that can 'distill individual experiences into a description of a universal essence' (Creswell and Creswell, 2018, p. 75). According to Merriam (1998), a case study methodology can seamlessly merge with other forms of qualitative research due to its inherent capacity for providing comprehensive descriptions. This methodological fusion underscores the central inquiry: What constitutes participants' interdisciplinary experiences and how do they perceive them?

2.2 Own interdisciplinary experience

In conjunction with the "phenomenological epochè" (Husserl, 1977), the pursuit of a self-conscious state is paramount, as described by the author who articulates it as "apprehending myself purely: as Ego with my own pure conscious life, through which the entire Objective world exists and is precisely as it is for me." (p. 21). This endeavor prompts a responsibility for researchers to introspect on their own thoughts, emotions, and experiences concerning the research theme. Sharing these reflections with the readers of this paper bears great significance as it elucidates the origins of the researcher's interest in exploring this phenomenon through the lens of the phenomenological approach.

The deliberate intent behind conveying to students the sense of multi-competence, adept management of skills, and the cultivation of holistic life perspectives – both personally and professionally – fosters a personal optimism towards interdisciplinarity, a sentiment that is handled delicately in this study. The unfolding events within the analyzed class period also called for introspection. For instance, the process of devising interdisciplinary activities for the class evoked both delight and stress simultaneously, stemming from the aspiration to maintain the connections as pure and useful as possible. In this course, we explored the integration of novel learning activities and innovative pedagogical approaches to enhance interdisciplinary educational outcomes. Immersive learning experiences were promoted, such as interactive simulations available at the University of Colorado's PhET[1] and augmented reality experimentation with the use of open-source software Tracker.[2] Additionally, we purposely aimed to develop physics and mathematical modelling, critical thinking, and problem-solving competences, therefore most learning activities sought to start from a phenomenon related to the students' daily lives or relatable situations that could deeply contextualize learning. Perceptions of these activities were diligently documented within a reflective journal maintained throughout the 4 months duration of the class. Reflections proved instrumental in the subsequent analysis and delineation of the essence of students' interdisciplinary experience.

1 https://phet.colorado.edu/en/

2 https://physlets.org/tracker/

2.3 Participants

As advocated by Creswell and Creswell (2018), exploring a phenomenon within a cohort of individuals who have personally encountered it suggests the inclusion of a diverse group of 10 to 15 individuals. This rationale substantiates the unit of analysis for this study – a cohort of 12 students who collectively share an interdisciplinary experience within a first-year mathematics class offered by a university situated in northern Mexico. The course is conducted in English, catering to students enrolled in honors academic programs. The selection of the participant pool adheres to a "convenience" (Merriam, 1998, p. 63) sampling approach, chosen due to their shared involvement in the phenomenon under study and their varied academic program backgrounds. Furthermore, the selection encompasses students enrolled in a course where the authors have actively engaged in both the design of learning sessions and their execution.

An additional motivation for selecting this calculus group pertains to the resistance against traditional and mechanistic approaches to teaching calculus, observed among those who facilitated the learning process for the group. These facilitators champion student-centered methodologies and employ experimental resources and technology to enhance the learning journey. The instructors of the examined course meticulously crafted activities aimed at fostering the cultivation of interdisciplinary competencies, deliberately opposing pedagogical methods that might be incongruent with the nurturing of interdisciplinary experiences.

2.4 Data collection

Two principal techniques were employed to comprehensively capture and document participants' interdisciplinary experiences: a written open-questionnaire and a focus group protocol. For the written open questionnaire, the foundational inquiries proposed by Moustakas (1994) served as the cornerstone for constructing the specific questions related to the experience of interdisciplinarity. Collaborating with the teacher team, a questionnaire comprising four open-ended questions was meticulously formulated and administered during the initial month of the course. The questions encompassed: (1) In your mathematics class, what instances of ideas from other fields do you discern? (2) How do you recognize the application of mathematics within the context of your chosen field of study? (3) What factors shape your perception of mathematics in your everyday life? (4) Which real-life scenarios have facilitated your comprehension of the concepts covered in your mathematics class?

Regarding the focus group protocol, the two fundamental questions aimed to unravel participants' experience were posed to the participants, who were already familiar with the topic and theme. These questions were presented verbatim and left open to the participants' interpretation.

In conjunction with the primary data collection techniques aforementioned, a quantitative instrument for gauging interdisciplinary perception (Hernandez-Armenta and Dominguez, 2019) was administered. Additionally, meticulous records were maintained for each interdisciplinary activity conducted over the 4 months duration of the course. Researchers' participant observations were recorded in a reflective journal along with detailed field notes. An online collaborative journal for students was maintained, and visual documentation, such as photographs of various class activities, was also amassed. Ethical considerations were diligently upheld throughout the research process (Creswell and Creswell, 2018, p. 54), encompassing the completion of consent forms by all study participants and ensuring the safeguarding of their anonymity.

2.5 Data analysis

The research design adheres to the methodological framework proposed for phenomenological inquiries by Creswell and Creswell (2018, pp. 78–80), encompassing the following systematic steps:

1. *Determination of phenomenological perspective*. The initial step involved ascertaining the appropriateness of a phenomenological perspective to explore the research problem.
2. *Phenomenon identification and description*. Subsequently, the phenomenon of interest was meticulously identified and described in a comprehensive manner.
3. *Clarification of philosophical assumptions*. The distinct philosophical assumptions underpinning the phenomenological approach were carefully delineated and elucidated.
4. *Data collection from participants*. Data were gathered from participants who collectively shared first-hand experiences of the phenomenon.
5. *Generation of meaningful analysis themes*. By delving into the gathered data, key analysis themes were derived, encapsulating the core essence of the participants' experiences.
6. *Development of textual and structural descriptions*. Subsequent to establishing the analysis themes, the process involved constructing rich textual and structural descriptions that conveyed the nuanced layers of the phenomenon's essence.
7. *Presentation of the phenomenon's essence*. The culmination of the analysis process entailed the creation of composite descriptions that succinctly captured the essence of the phenomenon, resulting in an integrated and profound understanding.
8. *Presentation of findings*. The ultimate goal encompassed presenting the in-depth comprehension of the phenomenon's essence in written form, thus conveying a coherent and illuminating narrative.

For the progression of steps 5 through 8, the framework formulated by Moustakas (1994) (depicted in Figure 1) has been embraced, providing a structured methodology for categorization and description development, thereby fostering a comprehensive and insightful understanding of the phenomenon's essence.

3 Findings

In this section we present and elaborate on the discussion of the results.

3.1 Participants' experiences

To facilitate the analysis process, transcriptions of the video and audio recordings from the conducted focus groups were meticulously transcribed. Subsequently, the verbatim expressions that held direct relevance, extracted from these transcriptions, were organized. The qualitative data analysis software was instrumental in accommodating the flexibility of multiple data categorizations. A comprehensive node database was constructed, bolstered by pertinent expressions derived from the written questionnaire administered to the participants. The complete set of expressions (totaling 126) was utilized to facilitate its categorization into constituent units (23), as illustrated in Figure 2. Within this intricate framework, a total of nine invariant units emerged within the theme of "What I feel," five for the "What I do" aspect, and an additional nine for the "What influences my experience" topic. These units, extracted from the expressions shared by all twelve participants, collectively contributed to a nuanced and comprehensive exploration of their interdisciplinary experiences.

From these invariant constitutive units, textural descriptions were meticulously crafted to encapsulate the essence of what participants were experiencing. Concurrently, structural descriptions were meticulously developed to delve into the influences and modalities through which these experiences were navigated by the participants (as illustrated in Table 1).

Throughout the focus group sessions, an in-depth exploration of participants' perspectives and opinions concerning the attitudinal dimensions of their interdisciplinary experiences was undertaken. The discussions were guided by two central questions: "What attitudes, in your view, are closely linked to interdisciplinarity?" and "Which attitudes best encapsulate your personal mindset during mathematics class in the context of interdisciplinarity?" To visually depict the recurring responses from participants, a word cloud was generated (refer to Figures 3A,B). This graphical representation serves to provide a clear visualization of the prevalent terms shared by the participants.

Regarding attitudes towards interdisciplinarity, participants collectively endorsed the significance of maintaining an open-minded disposition, coupled with a proclivity for thinking innovatively, fostering creativity, and nurturing empathy – all of which were deemed crucial for fostering interdisciplinary practices within the classroom setting. When delving into their own personal attitudes towards interdisciplinarity, students further highlighted qualities such as curiosity, receptiveness, and respect for diverse perspectives. Notably, participants also candidly acknowledged the presence of counterproductive attitudes, including idleness and demotivation, which emerged as the most prevalent antagonistic outlooks.

4 Discussion

4.1 Towards the essence, invariant units, textural, and structural tangle

As the tapestry of textural and structural descriptions, found on Table 2, weaves together the once fragmented conversations, a holistic

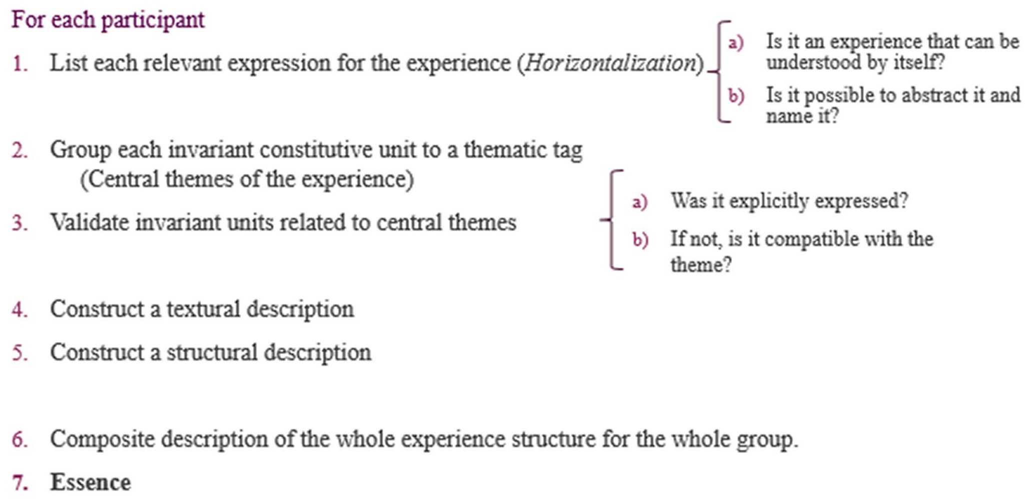

FIGURE 1
Moustakas' (1994) modification of Van Kaam phenomenological analysis method.

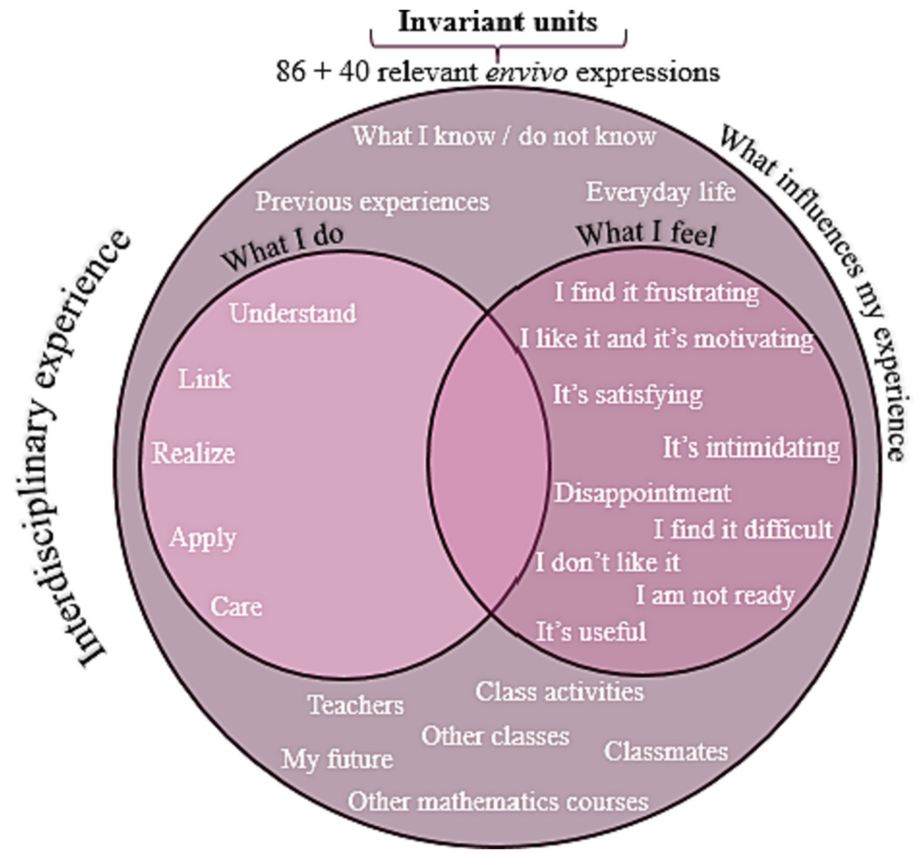

FIGURE 2
Invariant units for interdisciplinary experience of the Mathematics I group.

understanding of each participant's experience comes into focus. An intermediary stride in advancing toward the construction of the 'composite description' of the phenomenon (Creswell and Creswell, 2018, p. 201) involves interlacing the invariant units, textural nuances, and structural intricacies.

Within the process of making textural and structural descriptions, themes begin to coalesce, gradually illuminating pertinent facets that contribute to the overarching essence of the interdisciplinary experience. Other data collected items lend their weight to this phase, offering triangulation and reinforcement to

TABLE 1 Invariant units (What I feel, What I do, and Influences).

ID	What I feel	What I do	Influences
P1	-I find it frustrating -It's satisfying -I like it and it motivates me -It is intimidating	-Link -Understand -Realize	-What I do not know -Classmates -Previous experiences
P2	-I find it difficult -I like it and it motivates me -Disappointed	-Link -Apply -Realize	-What I do not know -My future -Previous experiences
P3	-I find it difficult -It's satisfying -I like it and it motivates me -It is intimidating	-Link -Apply -Realize	-What I do not know -What I know -Previous experiences
P4	-I find it difficult -I do not like it -I am not ready	-Apply -Realize	-What I do not know -Other mathematics courses -Class activities -Previous experiences
P5	-I find it difficult -It's satisfying -I like it and it motivates me -It is intimidating	-Link -Understand -Care	-What I do not know -Classmates -Previous experiences
P6	-It's satisfying -I like it and it motivates me	-Link -Understand -Apply	-What I know
P7	-It's useful -I like it and it motivates me	-Link -Understand -Apply	-What I know
P8	-It's useful -I like it and it motivates me	-Link -Understand -Apply	-Class activities -Classmates
P9	-It's satisfying -I like it and it motivates me -It's useful	-Link -Understand -Apply	-What I know -Previous experiences -Everyday life -Other courses -Classmates -Teachers
P10	-It's satisfying -I find it difficult -It's useful	-Link -Realize	-What I know -Previous experiences
P11	-It's useful	-Apply	-What I know -Previous experiences
P12	-I find it difficult	-Understands -Realize	-Everyday life -Class activities

underscore the relevance of these aspects in shaping the final composite framework.

4.2 Challenges in linking, understanding, and applying

A subset of participants – namely, Participants 1, 2, 4, and 12 – voiced a sense of interdisciplinarity as a challenge, articulating emotions ("What I feel" invariant units) such as frustration, intimidation, disappointment, difficulty, and even aversion. These emotions reverberate to impact their comprehension of class activities, application of mathematical concepts, and connection with other fields of knowledge. This sentiment is particularly prevalent among participants who grapple with two primary influences: gaps in their existing understanding and a lack of previous exposure to linking mathematics across disciplines.

For Participants 1 and 2, the inhibition stems from a perceived lack of foundational comprehension of mathematical methods, leading to a hesitance in initiating cross-disciplinary connections. As Participant 1 candidly expressed, "sometimes I'm like "damn, I do not know"." Participant 2 similarly shared, "since there are things I do not know, it influences my experience because I lack the foundation to make connections." This resonates with participants who find solace in sticking to familiar concepts, perceiving a lack of readiness to venture into interdisciplinary explorations.

Moreover, certain participants, such as 10, 11, and 9, have never previously conceived that mathematics could intertwine with other disciplines. Negative prior experiences with math classes have left participants 10 and 11 apprehensive, preventing them from conceiving any form of connection between their chosen career paths and mathematics. On the other hand, Participant 9, driven by a history of never making such links, finds motivation to persist in their attempts.

Participants 4, 10, and 12 encountered difficulties in the application of mathematical concepts from their class to other concurrent courses. These observations parallel Davies et al., 2010 viewpoint on the influence of past disciplinary knowledge on perplexing and frustrating experiences, disrupting interdisciplinary encounters. Additionally, the insights of Hall et al. (2018) on students' familiarity with discussed concepts and the confidence emanating from shared professional language contribute to shaping participants' varied experiences. This phenomenon may also impact student engagement and their perception of assessments, contributing to the intricacies of interdisciplinary exercises (Self and Baek, 2017).

4.3 Utilitarian value and practical application

For a substantial portion of the participants (P5, P6, P7, P8, P9, P11), their accounts of the interdisciplinary experience revolve around a profound realization, an emotional resonance, and cognitive connections that underscore the significance of mathematics as a practical tool extending beyond their class. These participants contemplate the potential applications of their mathematical knowledge across various subjects and projects, both within their academic journeys and their envisioned professional trajectories. A noteworthy observation is that these sentiments and actions are deeply rooted in the bedrock of existing knowledge – a secure foundation upon which new interconnections can be forged. As eloquently stated by Participant 8, "what you already knew, before what you are learning because you can then relate that, if you do not know it you obviously cannot relate it." Participant 9 echoes this sentiment, acknowledging that expanding knowledge allows for more intricate linkages with the familiar, stating, "if you have more extensive knowledge, I could not relate things with climate change because I did not know much and now that I know something, I can say that 'ah, it is similar to that."

FIGURE 3
(A) (left) and **(B)** (right). Word clouds from answers provided by participants regarding attitudinal aspects for interdisciplinarity **(A)** and for their personal attitudes about interdisciplinarity in Mathematics I class **(B)**.

For Participants 2, 5, and 6, the intertwined nature and real-world applicability of mathematical knowledge within their future professions and undertakings take precedence. They emphasize the value of these associations forged within the classroom, a testament to the importance of interrelating disciplines for personal and professional growth. Participant 6 eloquently encapsulates this sentiment, stating, "you do not ignore it, like, okay I already passed math I, check." Moreover, this interconnectedness also serves as a potent wellspring of motivation. As Participant 2 puts it, "for certain projects that I want to do, now I have more knowledge of some things, as they relate to what we are studying, so I always keep that in mind, so I can achieve the things that I do."

These insights align with Hero and Lindfors's (2019) observations concerning students' independent work and becoming "aware of" the usefulness of interdisciplinarity, as they active build team competences, agency of collaboration through communication and the competence of being aware of their own and collective learning and skills development. The recognition of the connection between interdisciplinary mathematical experiences and future endeavors is underscored by the articulation and value of interdisciplinary proficiency within professional work environments (Power and Handley, 2019). Additionally, the integration of theory and practice inherent in interdisciplinary approaches can cultivate heightened motivation, offering a clearer understanding of the purpose, value, and rationale behind learning activities. This integration encourages students to adopt an integrative approach to learning while envisioning themselves within their future roles (Munge et al., 2018).

4.4 Appreciation for interconnectedness

Several participants, including Participants 2, 3, 5, 7, 8, 9, and 10, enthusiastically express their fondness for the intricacies woven between mathematics and diverse subject areas. Their responses emphasized the realization that everything is connected, that mathematics can be applied in ways they have not imagined before. This newfound awareness fuels an elevated understanding of concepts, creating a web of understanding through the linking of disparate ideas. Moreover, this process triggers a sense of motivation, compelling participants to delve into the intricacies of natural phenomena with a broadened perspective. In the classroom, students were motivated to use technology to make connections and go deeper in their discussion (Figure 4). Participant 7 beautifully captures this sentiment "I really like how it is related to the class because mathematics opens up a landscape for all of us to be able to understand the same phenomenon and in some way describe it and predict what could happen."

Intentionally, class activities were designed to empower students to construct their own knowledge, fostering the discovery and decision-making process in shaping their personal understanding. Participant 9 articulates this sentiment "I really like that in class we do not just cover a topic and take it for granted because we just learned what to do, but we understand the uses so we can make links (…) at some point, we can relate it (what he learned) when we really need it."

Notably, participants 8 and 12 express contentment with the chosen thematic activities, embracing the diverse range that spans biology, natural phenomena, growth, cost, and economics. Their enthusiasm for these diverse themes echoes their embrace of interdisciplinary content and its applications in multiple contexts.

Remarkably, the transition from initial frustration to profound enjoyment is echoed by Participants 1 and 12, who highlight a remarkable shift in their attitudes toward interdisciplinary experiences. Initially, class felt daunting and perplexing, but the transformative power of interdisciplinary learning soon imbued it with a sense of enjoyment and illumination. As Participant 1 candidly notes, "before, class seemed frustrating, now I'm like "I love math class!", it's awesome, I get how the world works."

These nuanced responses resonate with the findings of Hero and Lindfors (2019), who spotlight the duality of teamwork experiences. While some students relish the opportunity to reshape their professional identities and embrace adaptability, others grapple with self-esteem and self-management challenges, along with the intricacies of collaborative problem-solving. Much like their study, our research underscores the broader benefits of interdisciplinary engagement, allowing participants to recognize each other's competencies, experiences, strengths, and areas for growth, while simultaneously fostering a deepened appreciation for their own learning journey.

TABLE 2 Textural and structural descriptions per participant (reduced table).

ID	Textural description *What is being experienced?*	Structural description *How is the experience lived and what influences it?*	Attitudes towards interdisciplinarity
P1	Realized mathematics are difficult to link. Transitions from frustration to enjoyment. Transitions from not understanding to start linking.	Influenced by what she does not know and by classmates' competences. Influenced by others' field of expertise. Influenced by previous academic experiences.	Negativity, enthusiasm, curiosity.
P2	Finds it difficult to make connections. Likes mathematics and that is a motivation to link and understand. Realizing that mathematics was going to be connected was disappointing.	Influenced by lack of knowledge. Motivated by future projects.	Connections, many ways to do things, open-mindedness, blocking.
P3	Realizes that everything is connected and likes it. Applies mathematical knowledge and relates it with physics.	Influenced by previous knowledge. Bringing memories to class.	Resistance and openness to know.
P4	Finds it very difficult. Likes traditional mathematics, not ready for connections. Understands the importance, but it is not comfortable. Thinks mathematics is a world apart.	Comparing with other math classes. Influenced by class activities.	Optimism, idleness.
P5	Understands math in a better way. Cares about real life applications of mathematics. Spontaneously links math knowledge with everyday life.	Having positive previous academic experiences with interdisciplinarity. Influenced by past and present teachers.	Empathy, being open to knowledge, accepting help from others and questioning my results and others'.
P6	Gets a better understanding of math relating it with physics. Finds mathematics useful to think.	Influenced by his career choice.	Curiosity, reasoning and conformism.
P7	Understands mathematics as a tool. Likes relating mathematics.	Influenced by previous knowledge.	Curiosity, finding explanations, being an observer, being other points of view, creativity.
P8	Likes mathematics. Applies mathematics in many useful contexts.	Influenced by class activities. Influenced by classmates and teamwork. Influenced by what he already knows.	Lack of motivation and observer attitude.
P9	Makes useful connections. Realizes that math is everywhere, and that interests him.	Lacking previous experience relating mathematics with other fields. Connecting current classes. Knowing more, linking more. Influenced by present teachers.	Communication, problem solving, listening to points of view, tolerance and relating concepts.
P10	Makes connections between math and physics during class. Likes making those connections. Realizes that mathematics can be applied.	Negative previous academic experiences with mathematics. Lack of connections between math and other classes.	
P11	Understands mathematics as a tool that connects with other fields.	Lacks connections and uses for career path. Shaped by past experiences.	Optimism, idleness.
P12	Finds it difficult to spontaneously relate mathematics.	Disconnection with everyday life. Influenced by hands-on class activities.	

4.5 Synergy of mathematics and physics

The entwining of mathematics with other fields of knowledge emerged as a significant way in which participants immediately recognized the interdisciplinary presence within their learning journey. While a multitude of subjects shared connections with mathematical principles, it was physics that stood out as the most prevalent and impactful domain, enriching their math class experiences. For participants, the interplay between mathematics and physics was readily observable in instances where problems explicitly showcased connections to biology, chemistry, or physics. Participant 12 eloquently captures this sentiment "In math class, I sometimes see the presence of ideas from other areas. When problems directly state the connection to biology, chemistry, or physics, I can see the presence. Different lab projects have helped me. For example, physics labs help me understand concepts more, because they are a physical representation of math and have topics applied to it."

This fusion of mathematical and physical concepts led to a profound synergy, with some participants like Participant 3 expressing, "I am in mathematics (class) and I am always thinking about physics." This dynamic perspective opened new avenues for comprehending the natural world. Participant 6 beautifully elaborates on this realization "it is much easier to understand a topic because we see mathematics'

FIGURE 4
Participants using software tools to model harmonic movement from real life videos.

nature reflected in physics. I mean, we simply understand better because we can see it in another way."

However, it is important to note that not all participants shared the same enthusiasm for the fusion of mathematics and physics. For instance, Participant 2 experienced a sense of disappointment upon recognizing that mathematics and physics operated within their own distinct frameworks. She conveyed this sentiment, stating, "when we started to see physics a lot it was like "wow, I unenrolled physics to end up studying physics in math" so I was a little bit, I do not know." Despite her initial reservations, Participant 2 managed to embrace the situation by recognizing the applicability of this interdisciplinary encounter, sharing, "well, I've been trying to catch it up and I feel that it's useful that we see real-life applications."

These nuanced perspectives highlight the diverse range of responses to the integration of mathematics and physics, reflecting the complexities and richness of interdisciplinary experiences. Just as mathematics and physics intertwine, so do the participants' perceptions, forming a tapestry of understanding that is uniquely their own.

4.5.1 Perspectives on textbook mathematics

The participants' perspectives on the integration of mathematics with other disciplines revealed intriguing insights into their familiarity with different pedagogical approaches and their epistemological viewpoints. Participants 1, 2, and 4 not only emphasized the importance of possessing strong foundational knowledge in mathematics and other fields to establish meaningful connections, but also highlighted their preference for alternative methods of mathematical instruction. Participant 4's viewpoint captured this sentiment succinctly "I think that it's okay that we have to understand those things (connections) however, it's something I'm not used to, I was taught like "get the book out and solve problems"." This sentiment underscores the participant's inclination toward more traditional textbook-centered methods of learning mathematics, indicating a certain level of discomfort with the interdisciplinary approach.

Furthermore, Participant 4's remark, "I feel that we take those courses separately for a reason and mathematics alone, I mean, each one (subject) should have its own space," reflects an epistemological position that advocates for the preservation of distinct disciplinary boundaries. This perspective suggests a belief in maintaining the separation of subjects, potentially rooted in the participant's perception of the unique value and integrity of each subject.

In contrast to more interdisciplinary approaches, these participants appear to be more aligned with a traditional view of mathematics education, where mathematical knowledge is compartmentalized and learned through standalone methods. Their viewpoints shed light on the diversity of pedagogical experiences and preferences among students, underlining the significance of tailoring educational methods to accommodate varying learning styles and epistemological perspectives.

4.6 Influence of teachers and classmates

Relevant influences for each participant's experience were attributed to previous lived experiences, prior knowledge for making new connections, class activities, and other parallel courses. Furthermore, teachers and classmates were reported to have a strong effect on the construction of reported perceptions. Regarding students' perception about teachers, they assure to "find the tutors take this seriously. Every time we see a new topic, they give us examples of other areas" (anonymous). Some students indicated teacher's function directly linked to the way in which interdisciplinary was manifested, such as Participant 5, "it depends on the role that teacher plays because they motivate you to see things from other points of view, in other ways, or they can also demotivate you."

Not only the teachers, but other educative features like teaching methods and philosophies were mentioned when thinking about positive influences for interdisciplinary experience. As it gets illustrated with the comment of Participant 9 "teachers, the kind of teaching that is used here that it is not centered, or that if it is, they give you the opportunity to think, it is not a squared system and it helps you learn." Figure 5 shows the teacher interacting with the team on the right.

Concerning classmates interacting, they marked the influence of teamwork in having the opportunity to be aware of what others think and do, one aspect that was identified as an element for interdisciplinarity too. As Participant 8 mentioned "situations where you work in teams with other people that maybe have different perspectives or ways to approach the same problem," he is aware that personal interest matters because "each person can see or focus on something and at the same time be within same topic." Students' interaction is shown in Figure 6. Also, a teacher recognized the benefits of the classmates' interactions by mentioning that "because we have students from different careers, each has a different approach to math and different ideas on the application. The learning of this ideas can broaden one's horizon on math, how and where can they be helpful."

By contrast, one particular student (Participant 1) opened up that the influence of her classmates was not the most encouraging for her progress in the class: "sometimes I say, 'oh damn, that I do not know' and then I realize that my classmates do know and I feel left behind and excluded." Fortunately, she found her way out of negative thoughts and ended up having a more complete interdisciplinary experience: "as we move along the semester, I'm finding the associations and I say 'wow, that's cool' y I feel that the exclusion, or that part in which I feel bad, well it wipes off and I remember why I like math a lot."

The influence of classmates was also evident in participants' reflections. Collaborative work and interactions with peers provided opportunities for students to engage in interdisciplinary discussions, share diverse perspectives, and learn from each other's backgrounds and

FIGURE 5
Teacher guiding and motivating students in the classroom.

FIGURE 6
Students collaboratively working and sharing their mental processes with their classmates.

knowledge. The diversity of academic backgrounds and viewpoints within the student cohort enabled a rich exchange of ideas, contributing to a more comprehensive understanding of interdisciplinary concepts. As participants engaged in team-based activities and discussions, they became aware of the several ways in which different disciplines could intersect and contribute to problem-solving. This finding resonates with the research of Jennett et al. (2017), who emphasized the importance of forming balanced interdisciplinary teams and incorporating expertise from various disciplines to foster innovative and holistic thinking.

However, it is important to note that the influence of peers was not uniformly positive for all participants. Some of the students experienced feelings of inadequacy or exclusion when comparing their knowledge to that of their classmates. This sentiment suggests the need for supportive classroom environments that foster inclusivity and provide opportunities for all students to contribute meaningfully. As demonstrated by the journey of Participant 1 from initial frustration to later appreciation, creating a space for students to explore interdisciplinary connections at their own pace and gain confidence over time can result in more positive experiences.

4.7 Balancing influences for optimal engagement

Overall, the findings highlight the multifaceted nature of influences that shape students' interdisciplinary experiences. The role of educators in fostering an environment conducive to interdisciplinary exploration and the contributions of classmates in enriching discussions and perspectives are critical factors. Striking a balance between these influences, while respecting diverse epistemological viewpoints, can lead to more engaging and meaningful interdisciplinary experiences. The interactions between teachers, students, and content can create a dynamic and holistic learning environment that nurtures creativity, curiosity, critical thinking, and the ability to connect knowledge across disciplinary boundaries (Madina et al., 2023). By recognizing and harnessing the power of these influences, educators can effectively guide students on a journey of interdisciplinary discovery, empowering them to explore the interconnectedness of knowledge and its real-world applications.

5 The essence, interdisciplinary experience

According to Moustakas "The final step in the Moustakas (1994) phenomenological method is the intuitive integration of the fundamental textural and structural descriptions into a unified statement of the essences of the experience of the phenomenon as a whole" (1994, Ch. 5). After the analysis of certain emerging topics from the textural and structural descriptions, a composite one can now be made.

- Seems that a holistic understanding of a phenomena that is itself holistic represents a complex task yet to be made. The subjective truths that constitute the interdisciplinarity lived by the twelve participants during the first-year calculus course are just brushstrokes of an emerging educational impressionist painting.
- On one thing, some tracings delineate struggle and challenge bounded in the sometimes-dazed linkages made from mathematics to other fields of knowledge and to everyday life. On the other hand, some other brushworks show that most of the participants found in interdisciplinarity useful and pleasant experiences for mathematics understanding, that I venture to claim are going to walk along with them during the rest of their university trajectories. Previous academic experiences, prior knowledge and the influence of classmates and teachers represent the canvas in which this interdisciplinary experience is created, leaving then to creativity the defiance for teachers and educational researchers to experiment with new textures, colors, and interdisciplinary painting techniques.

This study contributes to the understanding of educational interdisciplinary practices by shifting the perspective from teachers to students. Through the lens of phenomenology philosophy, it delves into both the challenges and benefits of interdisciplinarity within higher education settings, offering a comprehensive insight into the phenomenon. By offering empirical evidence of interdisciplinary engagement in a calculus course, this work further enriches the field of interdisciplinary mathematics education.

- We presume that this type of qualitative reflective methods depicts a valuable route towards the grasp of complex educational phenomena such as interdisciplinarity in higher education contexts, and so represents an opportunity for other scholars to keep on including and understanding everybody's voice.
- The development of descripted calculus class and the writing of this article was of great growth for both students and teachers involved. Their collective and individual experiences stand as evidence of growth.
- The evidence offered in this work can benefit mathematics educators and educational researchers interested in the teaching and learning of mathematics. The analysis of student experiences yields implications for integrating interdisciplinary perspectives into higher education curricula.
- The arrangement of factors and influences at play within these experiences and juxtaposing them with prior research findings, this work also contributes to comprehending the development and cultivation of complex interdisciplinary thinking.

In conclusion, this study paints a vivid picture of the interdisciplinary journey undertaken by students in a calculus class. Just as an artist navigates various shades, techniques, and inspirations to craft their masterpiece, so too do educators and researchers navigate the nuances of interdisciplinary education. The canvas of interdisciplinarity in higher education is dynamic and multifaceted, awaiting the continued exploration and innovation of those who seek to enhance the educational landscape.

5.1 Limitations of the study

Recognizing that phenomenological research methods is context-specific, this paper provides a glimpse into a specific time, place, participants, and researchers involved in the studied experience. The study was conducted within a specific context, namely a college calculus class in northern Mexico, which may limit the generalizability of the findings to other disciplines, levels of education, or cultural contexts. Additionally, the use of self-report measures and qualitative analysis introduces the possibility of bias and subjectivity in participants' responses and the interpretation of data.

Furthermore, the sample size of twelve participants may restrict the variability of perspectives represented in the study. The use of convenience sampling could also impact the diversity and representativeness of the participant pool. Moreover, the study's focus on the experiences of students may not capture the perspectives of educators and administrators, who play a crucial role in shaping interdisciplinary curricula and pedagogical approaches.

5.2 Implications and future research

Despite these limitations, the study contributes to the growing body of literature on interdisciplinary education. The findings underscore the importance of creating supportive learning environments that promote interdisciplinary thinking and provide students with opportunities to make meaningful connections between diverse disciplines. Educators can draw insights from this study to design curricula that foster cross-disciplinary understanding and collaboration.

Future research could expand the scope of investigation to include a wider range of disciplines, educational levels, and cultural contexts. Additionally, exploring the perspectives of educators and administrators could offer a more comprehensive understanding of the challenges and opportunities associated with implementing interdisciplinary approaches in higher education. Longitudinal studies tracking students' attitudes and experiences over time may provide deeper insights into the long-term impact of interdisciplinary education on students' academic and professional trajectories.

Data availability statement

The datasets presented in this article are not readily available. Due to confidentiality, the raw data is only available to the research team. Requests to access the datasets should be directed to angeles.dominguez@tec.mx.

Ethics statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Tecnologico de Monterrey. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

IHA: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. AD: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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