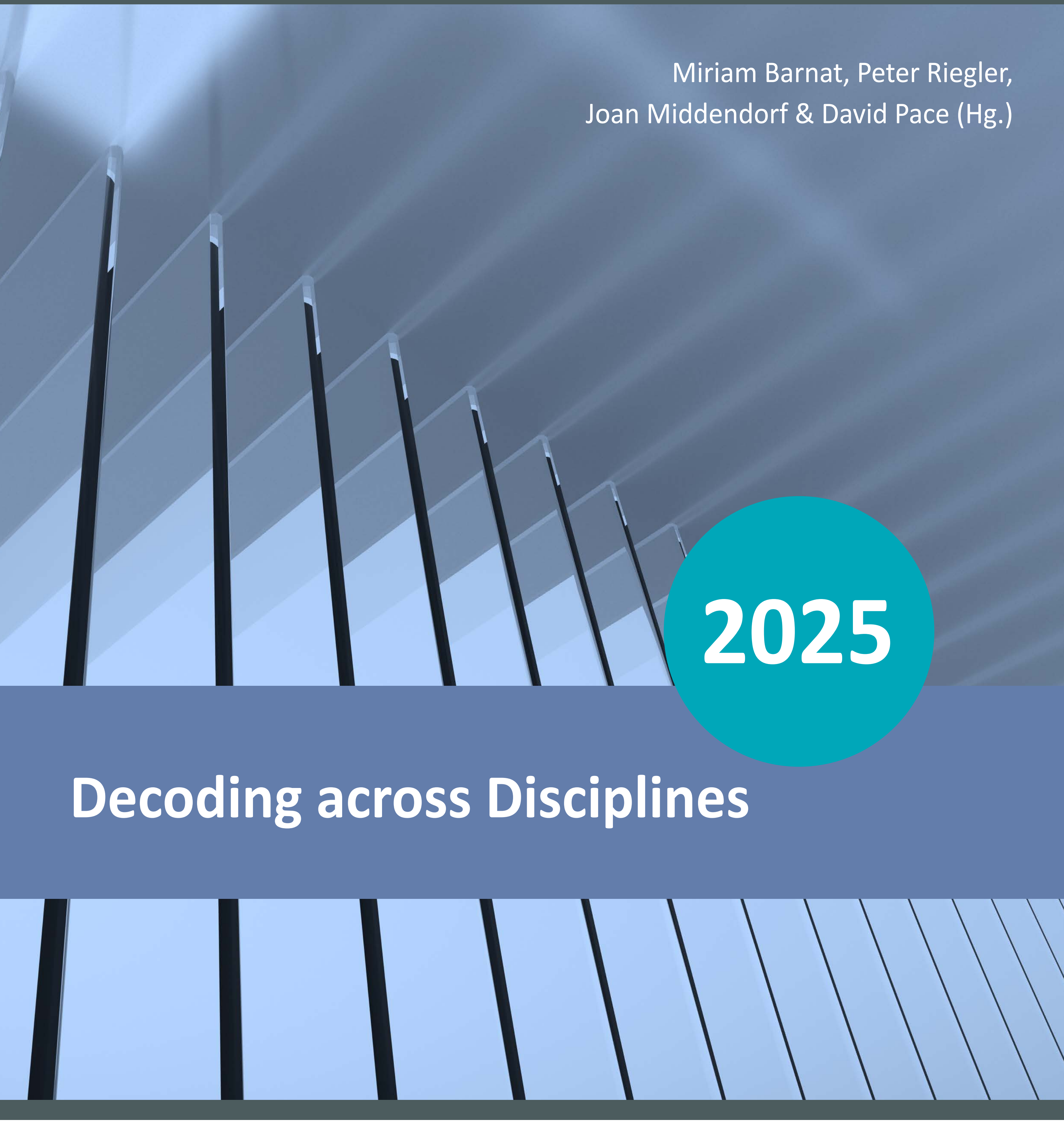
die hochschul*lehre*

Interdisziplinäre Zeitschrift für Studium und Lehre



Miriam Barnat, Peter Riegler,
Joan Middendorf & David Pace (Hg.)

2025

Decoding across Disciplines

wbv

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Miriam Barnat, Peter Riegler, Joan Middendorf, David Pace (Hg.)

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die hochschul*lehre* – Jahrgang 11 – 2025 (35)
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Editorial

to the special issue: Decoding across disciplines: New developments from all over the world

Miriam Barnat, Peter Riegler, Joan Middendorf, David Pace

Editorial

zum Themenheft Decoding über Grenzen von Disziplinen hinweg: Neue Entwicklungen aus aller Welt

1 Decoding the Disciplines

Disciplines are more than collections of specific knowledge; they can be understood as distinct cultures (Prediger, 2001) or tribes (Becher & Trowler, 2001), requiring students to navigate intercultural situations during their academic journey. Students enter universities with socialization rooted in everyday cultures and must adapt to the discipline's culture by building knowledge, developing competencies, and adjusting attitudes and behaviors. Learning in disciplines thus involves cognitive, emotional, and even embodied processes, making it insufficient to merely absorb abstract or canonical knowledge (Rhein, 2013).

The Decoding the Disciplines framework reflects this perspective by focusing on "bottlenecks"-specific obstacles that hinder student understanding (Pace & Middendorf, 2004; Pace, 2017; Middendorf & Shopkow, 2018). These bottlenecks often stem from the implicit knowledge of experts, who may find it difficult to articulate what students struggle with due to the "curse of expertise" (Brown et al., 2014). Through a structured, seven-step process, Decoding the Disciplines helps instructors make their implicit knowledge explicit and create targeted teaching strategies to support students in overcoming bottlenecks (Riegler, 2020). The steps include defining bottlenecks, decoding expertise, modeling tasks, creating active learning opportunities, motivating and lessening resistance, assessing learning progress, and sharing insights (Fig. 1).

- It enables experienced educators to gain new perspectives and innovate teaching methods.
- It fosters disciplinary thinking and supports students' expertise development.
- It facilitates collaborative changes in teaching across courses and disciplines.

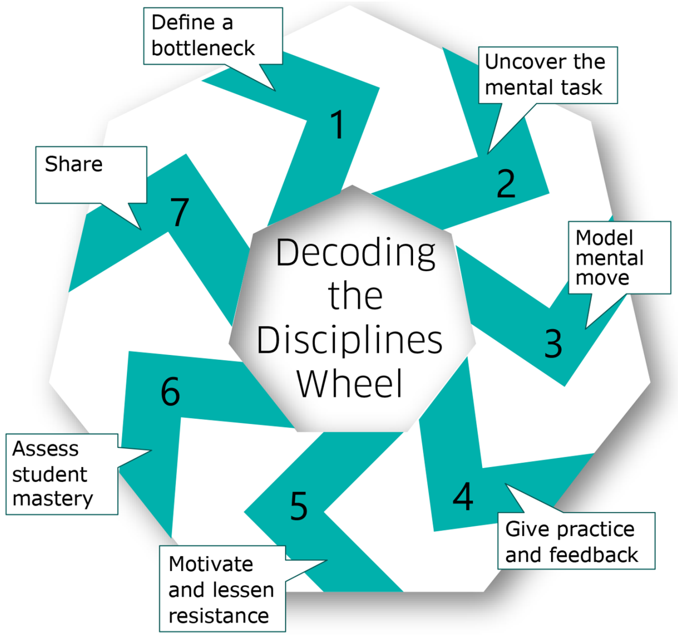

Figure 1: The Decoding the Disciplines Wheel

This framework offers several benefits:

The approach moves away from blame, recognizing that neither students nor instructors are inherently at fault for learning challenges (Kaduk & Lahm, 2018). Instead, it focuses on actionable strategies to bridge gaps between expert knowledge and student understanding. By grounding itself in the lived experiences of instructors and emphasizing the Scholarship of Teaching and Learning, this framework provides a practical, reflective, and collaborative approach to improving education within and across disciplines (Barnat, 2024; Waldherr et al., 2020).

Why would instructors and researchers at any level of education, in formal or informal settings, want to use Decoding? Instead of being overwhelmed with a firehose of ideas, Decoding takes a strategic approach that organizes research on teaching and learning. The framework prioritizes difficulties so that learning can be appropriately scaffolded and assessed to maximize student success. Starting from the bottleneck, one uncovers the mental moves that guide pedagogical choices. Decoding organizes theories and principles of learning and can serve as a solid start for scholarly teaching and for the Scholarship of Teaching and Learning.

Decoding the Disciplines is a promising approach to advance disciplinary university teaching in all its potentials (Chick et al., 2012). Since its conception in the late 1990s, the Decoding the Disciplines paradigm has provided a framework for a broad range of explorations of implicit teaching knowledge and practices. In particular, the Decoding interview process has allowed researchers to make more explicit the ways of operating that underlie work in specific disciplines. On the other hand, the methodology of Decoding also includes the aspect of creating and reviewing a teaching intervention (Shopkow & Middendorf, 2019). Another valuable contribution of the Decoding the Disciplines approach is that it enables research into the educational effects of teaching disciplinary thinking.

Furthermore, it is often not recognized that the paradigm has undergone enormous development since its appearance. The original model has been clarified and perfected, but the scope of this work was also expanded to include emotional, bodily, and social learning; it created new roles for students in these investigations; and it explored learning beyond the individual (Pace, 2021). The framework has been developed even further to use it as a tool for decolonizing disciplinary thinking (Lindstrom et al., 2022). These Disrupting Interviews helped them identify Eurocentric epistemological biases in their teaching practices.

Some of these changes have been so transformative that they may be regarded as a new iteration of the paradigm: Decoding 2.0 (Pace, 2021). This wealth of innovative approaches to utilizing Decoding the Disciplines to help students unlock their potential underscores the need for extended discourse within the field of education. To foster such dialogue, the first international Decoding conference was held in November 2023 in Aachen, Germany. Scholars from all over the world convened to present new bottlenecks, explore novel applications of the Decoding framework, and engage in discussions on Decoding and Disrupting the Disciplines. A selection of the conference papers underwent peer review and has been included in this special issue.

The Decoding community has now solidified and grown: a second international conference was held in 2024 in the United States; a wiki (Decoding the Disciplines, 2025a) was created to collaboratively gather knowledge about Decoding, complementing the website (Jong et al. (n.d.)) and YouTube channel (Decoding the Disciplines, 2025b). Another publication, focusing on scholarly reflections on Decoding the Disciplines, will be released as a special issue of DiNa (BayZiel, 2025) in the beginning of 2025. Furthermore, there is a collaboration with the journal *Transformative Dialogues: Teaching and Learning Journal*, ensuring that an issue dedicated to Decoding the Disciplines will be published annually. Additionally, there is an international Special Interest Group that meets monthly (details can be found in the wiki) and a German working group hosted by BayZiel. Everyone interested in contributing is warmly invited to join us in learning together and further developing the framework.

This special issue of *die hochschullehre* aims to highlight the connections between diverse approaches to Decoding while inspiring a new generation of scholars to further advance the paradigm.

2 The articles

The article by Itow et al. (2025) offers an important contribution to educational research and practice by describing the *Decoding Transitions to College* initiative, which bridges the gap between high school and college education. The initiative's uniqueness lies in its collaborative approach, where college professors and high school teachers work together to identify and address discipline-specific learning bottlenecks that hinder students during the critical transition to higher education. Using a design-based implementation research methodology, the project enabled educators from both levels to engage in structured dialogues and collaboratively identify shared learning challenges. The redesigned teaching and learning scenarios were conceptualized as well as implemented and reflected upon in real classroom settings. The article provides two concrete examples that illustrate the practical applicability of the developed strategies. Additionally, the project's commitment to supporting educators extended beyond the development phase, including dissemination activities such as mini-workshops. The article highlights the added value of collaboration between university instructors and school teachers, thereby illustrating the potential of Decoding the Disciplines as a driver of effective innovations across various expertise-driven systems.

Darcy's (2025) article is part of the *Decoding the Transitions to College Project* initiative described by Itow et al. (2025) and provides a much more detailed account of a specific bottleneck. It makes a significant contribution to educational practice by describing and evaluating an intervention aimed at improving first-year students' ability to interpret graphs-a key bottleneck in their transition to university-level learning. The intervention focused on first-year biology students and employed a graphing checklist developed through Decoding interviews. When implemented in an introductory biology course over two consecutive years, the tool proved highly effective. Beyond its practical impact, the article also highlights the crucial role of metacommunication in fostering student acceptance of and engagement with such interventions. By explicitly addressing students' thought processes and providing structured tools, the study demonstrates how tailored interventions can simultaneously improve competencies and gain acceptance. Importantly, the study illustrates how decoding-based interventions can inform teaching methodologies across disciplines, bridging gaps between secondary and tertiary education and fostering critical competencies for student success. By translating research into actionable teaching strategies, this article exemplifies the transformative potential of educational scholarship.

Cameron and Duffy (2025) also address the question of how students read graphs, albeit from the perspective of various other disciplines. Using the Decoding the Disciplines framework, the authors engaged faculty from three disciplines in decoding interviews, uncovering the mental steps involved in reading graphs. The study highlights that graph reading is an iterative rather than a linear process, challenging common assumptions among faculty that students intuitively understand graphical data without explicit instruction. A notable strength of the paper lies in its interdisciplinary approach, shedding light on both the similarities and differences in how various disciplines-such as chemistry, environmental science, and psychology-approach graph reading. This perspective not only deepens our understanding of the bottleneck but also provides educators with insights into how disciplinary contexts shape students' learning experiences. By carefully documenting how the decoding interviews helped faculty articulate their own expertise, the article demonstrates the broader potential of this methodology to refine teaching practices, address hidden challenges in student learning, and foster collaboration across disciplines. They make a valuable contribution to the field of quantitative literacy by addressing graph reading as a key bottleneck in students' academic development.

Pelnar and Cameron (2025) provide a third and novel perspective on graph reading by integrating two unique dimensions: 1. The involvement of student interviewers, offering a peer-led approach to data collection. 2. The focus on interviewing students themselves, providing insights directly from the learner's perspective. Involving students as both researchers and participants helps create a more accessible and equitable dynamic, reducing the risk of power imbalances and fostering open, authentic dialogue. One of the most striking findings is the misconception held by many students that graph reading is a skill one simply acquires naturally over time, without requiring specific expertise or deliberate effort. This misconception aligns with the observed difficulties students face in mastering graph reading. Experts allocate significantly more time to orient themselves within the graph, underlining the importance of deliberate and systematic engagement with the data. Many participants noted they had never been asked to reflect on their mental processes while reading graphs, highlighting a lack of metacognitive practice that may hinder the development of effective graph-reading strategies. The study also highlights directions for future research, such as exploring the alignment between faculty perceptions and students' actual strategies.

Elliot and Middendorf (2025) provide a valuable contribution to the understanding and application of the Decoding the Disciplines framework by focusing on its use in psychological statistics. It complements other studies in the collection by delving deeper into the structure of graphs and offering a detailed explanation of how pattern recognition functions in the context of graph interpretation. Notably, the article introduces an innovative alternative to the traditional Decoding interview-the Trading Analogies method-broadening the methodological toolkit available to educators. In addition, the article showcases the full cycle of Decoding, from identifying bottlenecks to implementing interventions and evaluating their impact. By emphasizing the advantages of cross-disciplinary collaboration and exploring various applications of Decoding in the Scholarship of Teaching and Learning (SoTL), this work underscores the versatility of the framework and its potential to enhance teaching practices across disciplines.

Finally, Nel (2025) makes an innovative and essential contribution to higher education pedagogy by focusing on emotional bottlenecks in learning-an often-overlooked but critical factor strongly intertwined with cognitive challenges. Emotional bottlenecks can hinder learning and lead to student resistance, yet they remain underexplored, particularly in technical fields such as computer science. The author introduces the Disciplinary Dream-Drawings (DDD) methodology within the Decoding the Disciplines framework, further innovating the latter by integrating visual and narrative approaches to uncover unconscious thoughts, emotions, and experiences. This pilot study conducted at a South African university involved first-year computer science students drawing their dreams and narrating their interpretations. The paper underscores the critical interplay between personal and academic challenges, offering valuable insights into students' behavior and guiding the creation of more supportive learning environments. Notably, a focus group allowed students to reflect on common themes and contributed ideas for improving computer science programs. In addition to exploring these bottlenecks, the paper provides practical recommendations for educators interested in implementing the DDD methodology. It highlights its potential to uncover hidden emotional challenges, inform pedagogical strategies, and enhance students' emotional and academic development. By addressing an area traditionally neglected in computer science education, this article represents an important contribution to the field and offers actionable strategies for educators seeking to better support their students.

3 Contribution to the field

In this outstanding collection of articles, some of the most significant advantages of *Decoding the Disciplines* as a framework become strikingly clear. The four articles on graph reading (Darcy, 2025; Pelnar & Cameron, 2025; Cameron & Duffy, 2025; Elliot & Middendorf, 2025) examine this skill from various disciplinary perspectives. While graph reading should not be assumed to be the only or most significant bottleneck, the analysis and exploration of this specific challenge highlight the framework's remarkable versatility. These four articles reveal both similarities and differences in how graph comprehension and interpretation can occur, providing valuable insights. Additionally, the inclusion of the student perspective offers a complementary viewpoint. Both perspectives-those of students and teachers-underscore that the traditional notion of learning as merely acquiring knowledge or practicing procedures is incomplete, if not fundamentally misleading. This shared blind spot perpetuates persistent learning obstacles and leaves education far from reaching its full potential.

Although science often revolves around numbers, facts, diagrams, and language, analytical thinking is not the sole pathway to accessing implicit knowledge or elevating teaching to a new level. Two articles (Elliot & Middendorf, 2025; Nel, 2025) emphasize the transformative potential of imagery-whether linguistic or truly visual-in addressing learning bottlenecks and enriching teaching practices.

Cameron's (2025) article, alongside those by Itow et al. (2025) and Elliot and Middendorf (2025), illustrates the transformative nature of engaging in deep interdisciplinary exchanges. One of the strengths of *Decoding the Disciplines* lies in its focus on active and intensive listening-embracing the unknown without needing to fully understand it and providing space for others to reflect. This process fosters new perspectives on the subject matter or teaching. At the same time, the listener benefits profoundly-first, through a sense of self-efficacy that sparks new ideas, and second, by discovering connections to their own work. These connections may stem from similarities across disciplines or entirely new ideas inspired by encountering the unfamiliar.

Although the foundational works by Middendorf and Shopkow (2018), as well as Pace (2025), have already explored the topic of emotional bottlenecks, the articles by Elliot and Middendorf (2017) and Nel (2025) in this volume offer fresh and exciting insights into this rich and expansive field.

On the one hand, *Decoding the Disciplines* is a deeply disciplinary practice, designed to address truly discipline-specific learning bottlenecks. On the other hand, several articles in this volume clearly demonstrate the benefits of transcending boundaries-whether between disciplines or between school and higher education. The introduction of new actors, such as students and teachers, into the framework opens up innovative ways to rethink teaching and learning.

Ultimately, the framework provides a robust foundation for interdisciplinary collaboration, as awareness of one's own discipline is a crucial prerequisite for constructive and impactful scholarly cooperation across fields. This makes *Decoding the Disciplines* an essential tool for shaping the teaching of the future.

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Decoding Transitions to College

Crossing the High School/College Frontier

Rebecca C. Itow, David Pace, Tara Darcy, Derek Chastain, Jahlea Douglas,
William Robison & Michael Beam

Abstract

This article presents the *Decoding Transitions to College* initiative, which aims to bridge the gap between high school and college through collaborative approaches. The program brings together high school and college educators to identify and address disciplinary learning bottlenecks that students face during the transition to higher education. The project was developed and refined using a design-based implementation research approach. Over multiple iterations, educators from both educational levels engaged in structured dialogues in two subjects per cohort, based on the *Decoding the Disciplines* method. The objective was to analyze learning challenges, uncover implicit expert knowledge, and develop strategies to support students in overcoming these obstacles. The article highlights the professional development activities of the participating educators and presents two specific learning bottlenecks alongside their solutions. By innovatively applying the *Decoding the Disciplines* approach in this collaboration, its potential to enhance teaching practices beyond higher education is clearly demonstrated.

Keywords: Decoding the Disciplines; pedagogy; transition to college; bottlenecks; biology

Entschlüsselung der Übergänge zur Hochschule:

Lernhürden an der Grenze von Schule und Hochschule

Zusammenfassung

Dieser Artikel stellt die Initiative Decoding Transitions to College vor, die darauf abzielt, die Grenze zwischen High School und College durch kooperative Ansätze zu überwinden. Im Rahmen des Programms werdenLehrkräfte aus High Schools und Colleges zusammengebracht, um fachliche Lernhürden zu identifizieren und zu bearbeiten, die Schüler:innen beim Übergang zur Hochschule begegnen. Das Projekt wurde im Rahmen eines designbasierten Implementierungsforschungsansatzes entwickelt und verfeinert. In mehreren Iterationen traten Lehrende beider Bildungsstufen in jeweils zwei Fächern pro Kohorte in den Dialog, basierend auf der Methode Decoding the Disciplines. Ziel war es, Lernhürden zu analysieren, implizites Expertenwissen offenzulegen und Strategien zu entwickeln, um Schüler:innen bei der Überwindung dieser Herausforderungen zu unterstützen. Der Artikel beleuchtet die Kompetenzentwicklungsmaßnahmen der beteiligten Lehrkräfte und stellt zwei spezifische Lernhürden sowie deren Lösungen vor. Durch die innovative Nutzung des Ansatzes Decoding the Disciplines in dieser Kollaboration zeigt sich dessen Fruchtbarkeit für die Weiterentwicklung von Lehre über die Hochschule hinaus.

Schlüsselwörter: Decoding the Disciplines; Didaktik; Übergang zur Hochschule; Lernhürden; Biologie

1 Introduction

The Decoding the Disciplines approach to enhancing student learning has spread across the globe, in large part because the basic paradigm can be adapted to respond to a great variety of challenges (https://decodingthedisciplines.org/; Middendorf & Pace, 2004; Middendorf & Shopkow, 2023; Pace, 2021; Pace & Middendorf, 2004). Yet the field and the larger scholarship of teaching and learning (SoTL) community have shared a self-imposed restriction that has limited its potential impact on the world of education; Decoding work tends to occur in post-secondary settings, and it can seem challenging to cross the high school/college frontier.

This paper describes one effort to cross that frontier. Decoding Transitions to College is both a program and a commitment: the program brings high school and college faculty together to share practices and unearth assumptions that could illuminate our understandings of the bottlenecks students face when transitioning to college. Our commitment is revealed in the active voice of our work's title: Decoding Transitions to College is an ongoing effort to Decode – or break down into its parts – the challenges that persistently prevent students from experiencing a smooth transition to college. In this work we position students' scholastic experience as a continuous arc of learning from kindergarten to college. Doing so has revealed specific transition-to-college bottlenecks, highlighted which skills are reasonable to expect in new college students, and invited high school teachers to use Decoding as a tool for improving their teaching.

From the outset, we aimed to involve the perspectives of as many central stakeholders as possible in our effort to understand the hurdles students encounter as they leave high school and enter a post-secondary environment. Across the leadership team, co-investigators, and participants, we ensured that administrative, student, and faculty voices actively contributed to every aspect of Decoding Transitions to College. The authorship of this paper is no exception. Table 1 describes the authors' roles and relevant experience to illustrate this point.

Table 1: Author Roles and Relevant Experience

Author	Initials	Decoding Transitions to College Role	Experience
Rebecca C. Itow	RCI	Research Team Leader	High school principal; university executive leadership; former secondary school teacher
David Pace	DP	Research Team Leader	A co-founder of Decoding; Emeritus Professor of History
Tara Darcy	TD	Decoding Transition to College Fellow	Senior Lecturer in Biology; Director of Undergraduate Environmental Studies, Integrated Program in the Environment
Derek Chastain	DC	Decoding Transition to College Fellow	High school biology teacher; college biology instructor
Jahlea Douglas	JD	Student Co-Investigator (2023–2024; 2024–2025)	Undergraduate student; academic coaching intern; current master's student in mental health counseling; high school assistant advisor

(Continuing table 1)

Author	Initials	Decoding Transitions to College Role	Experience
William Robison	WR	Student Co-Investigator (2022–2023)	Undergraduate student; academic coaching intern; current high school teacher
Michael Beam	MB	Research Team Lead	University executive leadership; former secondary school teacher; former secondary school administrator

Together, these stakeholders – as well as the other faculty participants – ensured that our exploration of the transition to college bottlenecks was informed by relevant voices.

Through five years of iterative Design-Based Implementation Research (DBIR; Fishman et al., 2013; Penuel et al., 2011) cycles, we developed a professional development (PD) structure that leverages "bottlenecks" in teaching (Pace & Middendorf, 2004) and the Decoding interview to engage educators in refinement of their pedagogical practices. We then used this PD structure with high school and college educators to explore what bottlenecks may be preventing students from transitioning to college smoothly. These research cycles generated three major outcomes:

a. a Decoding-focused sustained PD structure for exploring the transition to college;
b. valuable cross-level and cross-discipline dialogue; and
c. identification of three bottlenecks to the transition to college.

This article describes the structure of the Decoding-focused PD in the context of an effort to better understand the transition to college, how that PD supported high school and college educators in responding to pedagogical challenges by increasing communication between teachers in the two systems, and the bottlenecks to transitioning to college that were revealed. It closes with a discussion of how this work may evolve as we apply our learnings to practice.

2 Context

The work described in this article grew out of a concern with the number of students experiencing difficulty in introductory college courses – and in the transition to college more generally – as indicated by high drop, fail, and withdrawal (DFW) rates. Efforts to address DFW rates in introductory college courses are a priority both in U. S. research institutions broadly (Boyer 2030 Commission, 2022) and in the strategic plan of the university where this work was conducted. Author MB (university executive leadership) called RCI (a high school principal) and DP (a college professor) together to discuss this priority, and the resulting discussion made it clear that simply increasing communication between the two levels of educators may at least expose hidden assumptions and at best may offer insights for smoothing students' experiences in first-year college courses. Because of Decoding's strengths in promoting productive and disciplinary discourse (Engle, 2012) between diverse faculty, Decoding became the framework on which this work was built.

To identify and address transition-to-college bottlenecks (places where students tend to get "stuck"), we developed a program that framed student learning as a continuous journey from secondary through post-secondary education and recruited faculty from both sides of this "frontier" to share their experiences. Doing so highlighted differences in the training, institutional structures, and pedagogical practices across the two school levels. For example, in the United States, public high school teachers' training includes a focus on child development and domain pedagogy, while university faculty training is often focused on field-specific expertise (Baker, 2024). US public high schools tend to have a rigid bell schedule that tells students when to move, eat, and care for themselves, while universities expect students to manage their time and behaviors independently.

2.1 Decoding with Secondary School Educators

Decoding (Middendorf & Pace, 2004; Middendorf & Shopkow, 2023; Pace, 2021; Pace & Middendorf, 2004) leads educators through a process of identifying "bottlenecks" to learning or places in courses where students tend to "get stuck;" making explicit what students need to do to be able to get past these obstacles; and modeling, giving practice on, and assessing the targeted skills. Decoding as a process helps educators move beyond content and focuses their attention on the pedagogical decisions and moves an educator makes as they teach that content.

The Decoding interview has been a powerful tool for finding common ground as faculty inspect their teaching practices. In this process, a teacher identifies a place in one of their courses where significant numbers of students are unable to successfully complete essential tasks. Then the interviewers help the interviewee make the steps that students must follow to overcome this bottleneck explicit (Middendorf & Shopkow, 2023, 36–63; Pace, 2017, 32–53). Miller-Young and Boman (2017) found that when groups of teachers conduct Decoding interviews with each other, they develop a common understanding of the challenges that each face and a shared language for talking about teaching. This work, as well as the successful use of Decoding with preservice teachers at the elementary and secondary school levels (e. g., Díaz & Shopkow, 2017; Lovin & Schultz, 2012; McBrady, 2022) convinced us that Decoding with high school and college educators would likely reveal important insights around the transition to college.

2.2 Decoding Transitions to College

The first design cycle of this work began in 2020 as schools – and the planet – were figuring out how to keep students learning during the COVID-19 pandemic. To help teachers learn to teach online and build pedagogically sound virtual courses, RCI and MB launched a series of webinars, a graduate course, and a major state-funded online Course Design Academy. As part of this effort, middle and high school teachers engaged in the Decoding interview.

A second design cycle of the same model demonstrated that secondary school teachers had no difficulty identifying crucial bottlenecks in their courses, and responded to the Decoding interviews with the same level of commitment and insight that we had encountered at the college level. A middle school English teacher, for example, articulated the complex steps of choosing an appropriate personal experience for a personal narrative essay. A high school math teacher dissected the shifts in students' visualization processes when moving from geometry to trigonometry. It seemed that Decoding could support faculty across institutional levels as they inspected their own teaching. We therefore developed a sustained professional development experience that brought high school and college faculty together to Decode Transitions to College.

The third design cycle was titled Decoding Transitions to College, and was launched in spring of 2022. The directors of the program, RCI and DP, worked with an undergraduate student co-investigator (WR) to recruit sixteen dedicated biology and Spanish faculty, half from high school and half from college, as Fellows in the program (including TD and DC).

The fourth design cycle occurred in a second year of Decoding Transitions to College in 2023. This cycle used the same structures as the year prior, and invited educators from Chemistry and English to participate. A new student co-investigator, JD, joined the team.

The fifth design cycle in 2024 brought participants from the first two years of the Decoding Transitions to College program (design cycles 3 and 4) together. These educators designed professional development opportunities that could be delivered in their school contexts in a very limited timeframe. They then implemented their designs, introducing Decoding to a new set of audiences. Designs included a pamphlet on Decoding, worksheets and guides to find and address a bottleneck, a one-hour workshop for high school faculty on interviews and bottlenecks, conference presentations, an asynchronous virtual course using Decoding to support peer review among teachers at both the high school and university levels, and a department-wide high school PD series implementing the Decoding Transitions to College framework through regular Professional Learning Community meetings across the school year.

3 Method

This work occurred in five iterative design cycles from 2020–2025 with the four principles of Design-Based Implementation Research (DBIR; Fishman et al., 2013; Penuel et al., 2011):

1. **DBIR Principle 1: Teams form around a focus on persistent problems of practice from multiple stakeholders' perspectives**. Based on the Boyer 2030 Commission Report, the university strategic plan, and discussions with various stakeholders, RCI, DP, and MB identified this work's persistent problem of practice as the consistent struggles – or bottlenecks – that students experience during the transition to college, as evidenced by high DFW rates and first-year student retention rates. Each year of the project, the co-investigating team consisted of a high school principal (RCI), an emeritus professor (DP), undergraduate researchers and program assistants who worked with at-risk and first-year college students (WR and JD), and a member of university executive leadership (MB in 2022–2023; RCI in 2024–2025). Together, these stakeholders identified and recruited college and high school faculty in specific domains as project participants (represented by authors TD and DC), designed & implemented Decoding Transitions to College workshops, and made iterative refinements both within and across design cycles.
2. **DBIR Principle 2: To improve practice, teams commit to iterative, collaborative design**. Following the initial work in 2020, RCI, DP, and MB committed to engaging in several cycles of design and refined implementation of the workshop series. Each year, the team examined participant interaction within and across workshops to respond to participant needs and in pursuit of a finer understanding of specific bottlenecks to the transition to college.
3. **DBIR Principle 3: As a strategy for promoting quality in the research and development process, teams develop theory related to both classroom learning and implementation through systematic inquiry**. Decoding provided a systematic framework that guided the development and implementation of Decoding Transitions to College as well as individual participant engagement. At a broad scale, the Decoding steps helped us to develop an understanding of the challenge as well as to identify a general structure and starting point for the workshops. The Decoding steps also supported faculty in the difficult and vulnerable work of collaboratively inspecting their own teaching practice and identifying places for improvement (i. e., bottlenecks). Participant feedback and experience directly informed design and implementation at each stage.
4. **DBIR Principle 4: Design-Based Implementation Research is concerned with developing capacity for sustaining change in systems**. This work aimed to increase capacity within secondary schools and university departments to support students as they prepare for and embark on the transition to college. We did so by developing PD structures that use the Decoding framework to ease the flow of communication across institutional levels.

3.1 Recruitment of Participants

Program participants – called Fellows – were recruited by recommendation. Each iteration of the program involved 16 educators, with eight in each discipline. Of those eight, four were from the university level, and four were from the high school level. To begin recruitment, first we identified university departments that (a) teach first-year courses with (b) high DFW rates, and (c) have corresponding courses at the high school level. For example, university introductory biology had high DFW rates and biology is a required course at the secondary school level. We then worked with departments to identify university faculty who teach those introductory courses and consistently demonstrate a commitment to teaching. Recommended participants were then interviewed to determine selection.

Many of those college faculty chosen to be Fellows in the program had been involved in the university's dual credit program[1] . These faculty recommended high school teacher participants who would help them think deeply about the high school-college transition. Other high school teachers were recruited from design cycles 1–2's Course Design Academy.

3.2 Student Voices

Given that our ultimate goal was to understand and improve the transition to college, it was important that student voices were included in our research as well. Prior to the first year of the program, we interviewed students in introductory Spanish and biology courses regarding their experience in transitioning to college. We then shared excerpts from these interviews with the Decoding Transitions to College Fellows. The student narratives focused the Fellows on viewing their courses from a student's perspective, and made the differences in students' preparation for college across school systems with varying access to resources painfully visible.

We were unable to repeat these student interviews during the second year of the program; however, during both years, our student co-investigators (JD and WR) took part in all of the summer meetings and frequently contributed information about their own experiences.

4 Results

Decoding Transitions to College resulted in three major outcomes that offer concrete PD structures, practical guidance, and clear examples of how bottlenecks and the interview process can facilitate cross-disciplinary and cross-level dialogue that informs research.

4.1 Decoding-Focused Sustained Professional Development Structure

The first major outcome of the Decoding Transitions to College work is a refined professional development structure that uses the Decoding framework to support sustained learning in community. The PD occurred over a full year on this timeline:

- Asynchronous week of introductions to each other and Decoding content (early summer)
- Synchronous two-day workshop to commune and further explore the Decoding steps and experience (Step 1) Defining a Bottleneck and (Step 2) Uncovering the Mental Task (early summer)
- Semi-synchronous interviews, pedagogical discussion, and curricular strategy development (1–2 summer months)
- Asynchronous implementation and refinement, leaning on community as needed (academic year)
- Synchronous one-day meeting to share experiences (spring)

Within this timeline, we designed and implemented these structural components of the PD:

1. *In stakeholder teams, identify a persistent problem of practice.* In this work, the persistent problem of practice was understanding the transition-to-college bottlenecks that prevent students from achieving in introductory courses. The bottlenecks identified were, in themselves, deeply rooted persistent problems of practice as well.
2. *Convene stakeholder participants with practical expertise from varied fields and institutional levels.* We gathered administrators, researchers, faculty, and students with expertise in how people learn at secondary and post-secondary institutions to explore the transition to college collaboratively. Each participant (including the research team leaders) cared deeply about improving teaching and learning.

1 The university's dual credit program offers introductory college courses in high schools. University faculty design the course and train teachers to deliver it to students at their local high schools, where students can earn high school and college credit simultaneously.

3. *Build community*. Before discussing bottlenecks or Decoding, we started with the human, inviting participants to share their professional experiences and goals. We worked under the notion that before we can engage in the hard work of learning, we work to create an environment in which participants feel safe, supported, and connected to one another (Kennedy, 2023; Fig. 1).

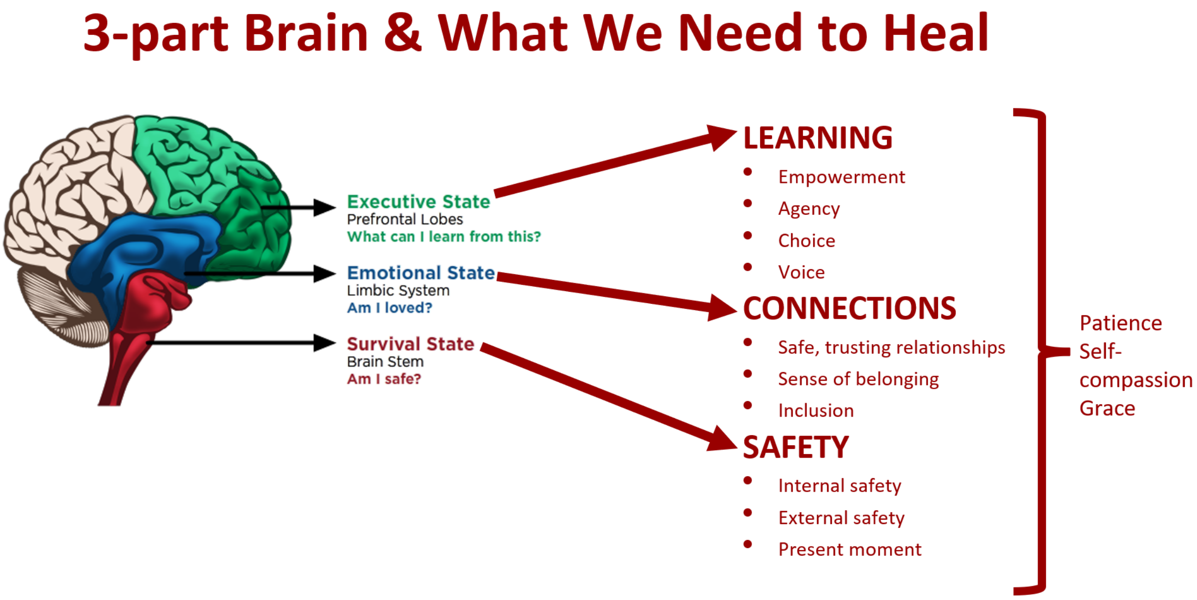

Figure 1: 3-Part Brain & What We Need to Heal (Kennedy, 2023; image reprinted with permission)

4. *Introduce bottlenecks through a Decoding interview and debrief*. Only after the group became familiar with one another did we introduce Decoding. After a brief introduction, we invited volunteer interviewees and interviewers to model how to identify a bottleneck. Conducting an interview with spontaneous volunteers helped to demonstrate both how to search for a bottleneck, and that one can identify a challenge in their teaching without diminishing themselves as a professional or a human.
5. *Discuss pedagogy and practice in cross-disciplinary/cross-level teams*. Once the large group interviews were complete, cross-disciplinary and cross-level teams of four rotated through the interview roles (interviewee, interviewers, scribe) until every participant had assumed each role. As they did so, participants began unearthing bottlenecks, identifying their common themes, and noting unique characteristics.
6. *Develop cross-cutting curricular strategies in interdisciplinary/cross-level teams and individually*. With bottlenecks defined, participants gathered in interdisciplinary/cross-level teams to brainstorm and develop cross-cutting curricular strategies that address a specific curricular issue and can be applied within domains and across levels.
7. *Implement, gather feedback, refine, repeat*. Individual educators then implemented their designs in classrooms, gathered feedback and collected work from students, refined their strategies, and repeated the cycle until they were satisfied with the results.
8. *Share experiences and student responses*. All stakeholders gathered to share their experiences, push on each other's thinking, and learn from one another. Participants identified similarities in implementation and discussed further refinements as a group.
9. *Analyze and apply results to persistent problem of practice*. The group's insights then informed our understanding of the bottlenecks for transitioning to college.

4.2 Fruitful Dialogue

A second major outcome of this work is the valuable cross-level and cross-discipline dialogue that focused on pedagogical refinement within course contexts.

4.2.1 High School Biology Example

DC, a high school biology teacher, found that his participation in Decoding Transitions to College fundamentally reshaped his pedagogical thinking. His interview revealed that students were omitting crucial steps when visualizing concepts in three dimensions, and DC realized that this was because parts of the process were missing in his instructions. DC shared that "After the Decoding [interview] process, I realized that this is more of a visualization problem. I am trying to train these students to think like a biologist and to visualize or imagine in three dimensions. I am now aware that there is a lot more involved, that there are a lot more steps in my mind." DC began to carefully cover each step and increase opportunities to receive feedback from students.

DC was also inspired to refine his strategies by a phrase that had become a kind of mantra for Fellows in his discipline – "Biology is not a spectator sport." DC realized that the polished PowerPoint presentations he had developed might not be working because they allowed the students to remain passive "spectators" in the learning process. Therefore, DC replaced some of the presentations with active-learning exercises involving work on the board, making cardboard cutouts, and crafting pipe-cleaner models. He showed the students how to model the phenomena being described in lectures as a way to articulate the concepts being learned. DC developed a classroom culture in which students were encouraged to ask more questions, and this helped him better recognize when students were encountering bottlenecks. He also administered questionnaires to better understand how students were integrating the learning procedures that he was modeling into their study practices.

4.2.2 College Biology Example

A second pathway through the Decoding process was charted by TD, an instructor in the Biology department at the university. She began her Decoding interview by expressing her dismay that many of her students were having difficulty interpreting graphs that seemed quite obvious to her. However, after throwing herself into the process, TD dissected the process into a complex series of subtasks and realized that what she was expecting of students could actually be quite demanding for novice learners.

Recognizing that this step was essential for her students' success in the course, TD identified three stages that were required for success at the task of understanding a graph in an introductory biology course: orientation (e. g., identifying independent and dependent variables), pattern recognition (e. g., describing the shape of the function-linear/non-linear; increasing/decreasing), and interpretation (e. g., why the function was changing in this way; identifying intercepts or equilibria; and connecting it to relevant biological concepts). Each time a new graph was introduced, TD guided the class through each subtask in a "graphing checklist" that she developed from her engagement with the Fellows, allowing the students to answer some of the questions on their own while ensuring they had the correct interpretation by the time they left the class. The students could use these checklists on homework and online quizzes or even apply the subtasks to graphs encountered in other science classes. In a survey of 297 students, 78.5 % of them indicated that the graphing checklist tool had been valuable for their learning (Darcy, 2025).

4.2.3 More Examples of Pedagogical Change

There are numerous examples of similar specific initiatives that the Fellows undertook in their courses as a direct response to their participation in Decoding Transitions to College. Several Fellows indicated that they were now focused on the need to be "more transparent" in all of their interactions with students. One Fellow restructured homework assignments to more clearly model and give practice on key mental operations. Many Fellows collaboratively developed strategies for modeling note-taking, and one Fellow had students peer-review their classmates' notes. Another restructured a course so that each week they focused on a bottleneck.

4.3 Transition-to-College Bottlenecks

A third major outcome of Decoding Transitions to College is the identification of three bottlenecks first-year students experience when struggling with the transition to college. At the conclusion of the 2023–2024 iteration of Decoding Transitions to College, Fellows from both cohorts were invited to return to share how their teaching had continued to evolve, and to build relationships across cohorts. In addition to presenting specific interventions designed to help students master particular skills, the two cohorts articulated three broader bottlenecks to the transition to college, which will be a focus of future work:

1. Becoming an independent learner and trusting oneself and others
2. Exhibiting professionalism and executing time-management skills
3. Engaging in practices that promote motivation, persistence, and resilience

In each of these bottlenecks, the Fellows identified specific behaviors that need to be consciously modeled for students in the learning environment before and after the transition to college.

5 Discussion

Equally indicative of the impact of this work were the Fellows' reflections on the how their teaching changed as a result of Decoding Transitions to College. The Fellows' general reactions to Decoding were overwhelmingly positive. Both the high school and the college faculty volunteered terms like "super helpful," or "mentally charged." Another commented that she "wasn't really expecting to get such great ideas ... I had a project. I thought I knew what I was doing and then I got these fantastic ideas that have worked so well."

5.1 Impact of Cross-Discipline and Cross-Level Insights

During a 2024 meeting with the Fellows, several commented on the ways that working with people outside their disciplines led to new and often unexpected insights. A chemistry professor, for example, commented on how much the process of interacting with the high school English teachers had given her important insights into what made her subject difficult for many students. Another college faculty member stressed the importance of "finding out what was ... different between what they're doing at the high school level and the college level." In a group discussion, a Spanish professor made connections between her students' struggle with language and those articulated by a high school chemistry teacher.

Perhaps what was even more striking was the fact that so many of these high school and college faculty spontaneously reported that the program had fundamentally transformed their teaching. This is particularly significant because this was a group of educators who had been selected because of their years of experience in the classroom and their effectiveness as instructors. The term "holistic" was used repeatedly to describe the impact of the program. Fellows described the approach as "a whole new state of mind. . . a [new] thought process in terms of everything that I present." One fellow reported that Decoding had changed "my teaching in a way that I didn't expect." Another described the approach as a process that now "overarches" everything. One high school teacher noted that in addition to the planned applications of the approach, there were often "accidental" occasions in which Decoding allowed her to respond to challenges that emerged unexpectedly in a different way than she might have before. Yet another said that she took away "a different philosophy, where I'm becoming more myself as a teacher." And many of the Fellows indicated that they were changing their teaching strategies, not only in the courses they had targeted in the program, but in others as well.

5.2 Considerations for Sharing Decoding Rapidly

At the conclusion of the 2023–2024 workshop, participants made clear that, while they want to share both the strategies they developed and the Decoding framework itself with their colleagues, they are unsure how to do so in the time-limited settings available in their individual institutions. Additionally, concerns were expressed about how receptive their peers might be to this process, given that the Decoding Transitions to College participants were selected by recommendation and based on their likely receptivity to this type of personally vulnerable work.

In response to these Fellows' requests for tools to share the investigative techniques they have learned with their local colleagues, the next cycle (design cycle 5) was refined to engage returning Fellows in developing "mini workshops" that can be deployed in 45-minute or one-hour sessions (described in Section 2 above). Fellows designed professional development experiences and resources that offer tools for supporting the kind of pedagogical exploration that they found so helpful without requiring significant external, time, or financial resources. In this way, Decoding Transitions to College simultaneously works to further build capacity within secondary schools and university departments while continuing to explore bottlenecks to the transition to college.

6 Conclusion

Many of the Decoding Transitions to College Fellows have commented that the focus on bottlenecks to learning had become a central element of their pedagogies. One noted that "... spending time on that one bottleneck early in the course has really reaped tremendous benefits that I couldn't predict down the line." Bottlenecks have permeated the Fellows' consciousness to such an extent that, when one of them commented that she now saw her relationships with her husband and her children through a bottleneck lens, many of the other Fellows indicated that the same was happening in their lives. One of the college chemistry teachers, for example, created special "Bottlenecks Friday" sections of her course to help students with difficult challenges. When another Fellow had made two crucial bottlenecks the focus in all sections of a course and all assignments throughout the semester, she was surprised to find the number of "A"s achieved by her students that year had increased by 9 % over the previous year.

Such responses, in addition to the quality of the interviews, the effective collaborations across disciplines and across the high school/college frontier, the production of new course activities and assignments, and the willingness of the Fellows to share what they have learned with others outside the program, provide ample evidence that the basic elements and structures of Decoding Transitions to College are sound. The focus on bottlenecks and the Decoding interview process provided both a stimulus to major pedagogical innovation as well as a framework for communication between educators at the two levels. These may prove crucial in smoothing the transition from high school to college courses.

Furthermore, the use of Decoding to bring high school and college faculty together has empowered educators at both levels; throughout the workshops, Fellows have shared that they see their teaching and themselves in a new light because of the relationships they built in this program, that their colleagues and administration are impressed with their work, and that their relationships with students have improved. Several Fellows have integrated Decoding into other, more advanced courses, and some have used what they learned to initiate new projects at the university. The research team leaders, too, have found that the insights gleaned from engaging multiple stakeholders in our exploration of the transition to college have impacted the shape of our research and program development. The model developed in Decoding Transitions to College opens up an entirely new horizon for the application of Decoding and for the scholarship of teaching and learning more broadly. It can play a major role in our efforts to provide students with the preparation they need to succeed in our educational systems and in their lives beyond.

Gratitude note

The work described here is the result of collaborative efforts from all of the Decoding Transitions to College Fellows. We are grateful for the Fellows' work to decode transitions to college, and appreciate the time and expertise they have shared to move this effort forward.

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Enhancing Graphical Literacy in Introductory Biology Students using the Decoding Disciplines Paradigm

Tara Darcy

Abstract

In 2022, the Indiana University *Decoding Transitions to College Project* united high school and university instructors to identify bottlenecks in student learning that interfere with transitioning to university. I focused on a challenge experienced by many university students-interpreting graphs. Using Decoding, I developed a graphing checklist outlining steps to interpret graphs, including ***orientation*** (identifying variables), ***pattern recognition*** (describing function shape), and ***interpretation*** (explaining the biological context of graphs). The checklist was implemented in an introductory course in 2022 and 2023. Students were guided through its use during discussions of new graphs. Over 75 % of students found checklists useful for interpreting graphs in several potential contexts. Additionally, significant improvements were observed from pre- to post-semester assessments of graphing skills. This intervention highlights a practical application of Decoding to enhance graphical literacy, a critical competency for scientific success, and demonstrates the effectiveness of translating Decoding into actionable teaching strategies.

Keywords: Transition to university; biology; graphing literacy; Decoding the Disciplines; intervention

Verbesserung der Datenkompetenz von Biologiestudierenden im Grundstudium durch Decoding the Disciplines

Zusammenfassung

Im Jahr 2022 brachte das Projekt „Decoding the Transitions to College“ an der Indiana University Lehrkräfte von High Schools und Universitäten zusammen, um Lernhürden zu identifizieren, die den Übergang zur Universität erschweren. Eine zentrale Lernhürde bei Studienanfängern war die Interpretation von Grafiken. Durch Dekodierungsinterviews entwickelte ich eine Checkliste, die in drei Schritte unterteilt ist: **Orientierung** (Identifikation unabhängiger und abhängiger Variablen), **Mustererkennung** (Beschreibung des Graphen) und **Interpretation** (Verknüpfung mit biologischen Konzepten). Diese Checkliste wurde 2022 und 2023 in einem Einführungskurs für Biologie eingesetzt. Studierende wurden angeleitet, neue Grafiken mit der Checkliste zu analysieren. Über 75 % der Studierenden berichteten, dass die Checkliste hilfreich war, um Grafiken zu verstehen und zu interpretieren. Zudem verbesserten sich die Datenkompetenzen in Evaluierungen vor und nach dem Semester signifikant. Diese Studie zeigt eine erfolgreiche Intervention zur Förderung von Datenkompetenz, einer zentralen Fähigkeit für wissenschaftliches Arbeiten, und verdeutlicht die praktische Anwendung des Dekodierungsansatzes.

Schlüsselwörter: Studieneingangsphase; Biologie; Datenkompetenz; Decoding the Disciplines; Fachdidaktik

1 Introduction

Academically challenging transitions are an inevitable component of the first-year university student experience. As universities continue to recognize this challenge, in tandem with related social and emotional transitions, faculty and staff are becoming increasingly aware of the need to directly address the transition-related obstacles faced by our incoming students. As an instructor of a large-enrollment (60 to 300 students, depending on the section) introductory biology course at a large university in the United States, I have consistently encountered a number of foundational skills with which my students struggle, particularly those students that are new to collegiate-level academic expectations. Indiana University is a state school in Bloomington, Indiana, with a student body composed of over 69,000 undergraduate students and over 20,000 graduate students. The biology major boasts over 1000 undergraduates spanning first- to fourth-year students.

My introductory course for biology majors (Biology L111 Foundations of Biology: Diversity, Evolution, and Ecology; hereafter, "Biology L111") introduces these three sub-fields of organismal-level biology using a quantitative and analytical approach to course content. Incoming students are expected, but not required, to be well versed in at least algebra and have reached an intermediate level of graphical literacy. However, even prior to the COVID-19 pandemic, I was consistently confronted with the fact that my students were not equitably equipped with these skills. This variation in skill set is likely related to the lack of high school or university prerequisites for Biology L111. As long as the student has passed one general biology course in high school, they can enroll in Biology L111.

Undergraduates often struggle to understand the graphs presented to them during course lectures (Bowen & Roth, 1998). Students can face several difficulties when interpreting a graph; these can involve issues related to the format of the graph or the level/type of prior knowledge of graph content (Shah & Hoefner, 2002) as well as becoming intimidated by the amount of information conveyed on the graph (Glazer, 2011).

Based on my own survey data, over 70 % of my introductory biology students are interested in graduate school or medical professions. Understanding, interpreting, and creating visual representations of data, information, or models (i. e., data literacy) are crucial skills necessary for every career in science, technology, engineering, and mathematics (STEM) as well as all medical professions.

To succeed in their chosen field, as a student and as a professional, one must immerse oneself in the relevant primary literature, most of which will contain graphical representations of experimental results. Every scientist will eventually need to interpret those graphs to better inform their own research, and they will certainly need to produce clear representations of their own data. Every physician will not only need to interpret graphs that present results of clinical trials, but they will also have to understand and explain graphs of test results to their patients. If a student takes Biology L111 in their first semester of university, the class represents the first step toward these careers, and if poor graphical literacy goes unchecked, students may struggle in upper-level biology, chemistry, and physics classes, all of which are requirements of the biology major at most universities; they may in turn exhibit poor performance on entrance exams; and in some cases, their intended career path may become unattainable.

Graphs can be encountered in other facets of our lives outside of academia or professions. Hence, everyone benefits from a basic understanding of orienting oneself to a graph. As consumers of media, we must be able to recognize when the scale or units of graphs have been modified to misrepresent information, perhaps to show a difference when one does not actually exist. A foundational level of graphical literacy is an essential component of critical thinking and differentiating fact from fiction.

Based on the myriad of ways in which individuals encounter data, information, and graphs, researchers have begun to recognize the need for educational interventions to improve data literacy (e. g., Glazer, 2011; Gebre, 2018). Several such interventions have recently been put forth for use in the classroom (e. g., Gardner et al., 2024).

In my classroom, I observed that the gaps in my students' understanding of graphs were particularly wide in our discussions of ecological models. Students are typically quite surprised that ecology, the study of interactions among organisms, can be both quantitative and analytical, and they frequently have difficulty interpreting the relevant graphical representations of models of ecological processes (e. g., D'Avanzo, 2006). This struggle was most obvious when analyzing the results of summative assessments such as in-person, closed-note exams. Yet, similar results were also observed for online, open-note exams during and after the pandemic. In particular, I noted low performance on exam questions that involved analysis of graphically represented course concepts, particularly topics related to population growth models. Specifically, only 20 % and 40 % of students were able to correctly answer a relatively difficult question on paper and online exams, respectively. This question of interest was especially challenging because it required students to analyze the graph provided yet answer a question about a related graph that was not shown. The question was meant to assess whether students possessed a deep understanding of the population growth model represented in the graph. The low scores on these types of complex graphing questions may be related to the propensity of students to view graphs as simply a picture rather than an abstract representation of a scientific concept or phenomena (e. g., Hadjidemetriou & Williams, 2002).

All too often, students who encounter challenges early in a course will respond to their frustration by giving up and investing increasingly less effort into the course, the ultimate reasons for which can vary from individual identity triggers (Lund Dean & Jolly, 2012) to science anxiety (Rozgonjuk et al., 2024) to the culture fostered in the classroom by the instructor (Muenks et al., 2024). Ultimately, a fraction of students can be "lost," either from the class or even from the major. Such attrition is often measured using "DFW" rates, which account for all students who have received failing grades of "D" or "F" or who have withdrawn (W) from the course. During the spring semester of 2021 (prior to the work described herein), the DFW rate for my Biology L111 course was 22.3 %. Students who comprise this statistic inevitably feel a sense of failure and may even be placed on academic probation, which can affect scholarship eligibility. These consequences may further impede the pursuit of their career goals, both personally and economically, and can sometimes lead to leaving university altogether.

It was with four years' worth of frustrating assessment results that I began to work with the Decoding the Disciplines community at my university. I was invited to participate in the *Decoding Transitions to College Project* during the summer of 2022. As a Fellow in this workshop, I worked with university colleagues in biology and Spanish as well as high school teachers in both disciplines to apply the Decoding the Disciplines paradigm to bottlenecks (i. e., obstacles) in student learning that we jointly identified as being most common to our respective groups of students. This paradigm was developed by a group of faculty beginning in the 1990s as they collectively realized that their current methods were not adequately teaching students the skills they needed to succeed in their respective fields of study (Pace & Middendorf, 2004; Middendorf & Shopkow, 2017; Pace, 2017; Pace, 2021). Since its development, the paradigm has been introduced to higher educational universities and facilities around the world. By the 2020s, when the above-mentioned issues involving the transition from high school to college were gaining attention within higher education circles, one of the original developers of the paradigm, along with the principal of the online Indiana University High School, began to explore the applicability of Decoding the Disciplines within K-12 (primary and secondary education) classrooms. These initial explorations highlighted how well middle and high school teachers responded to applications of Decoding in their classrooms, and hence a faculty member and administrator launched the first *Decoding Transitions to College Project (*Itow et al. *2025)* to bring together high school and university instructors to strategically and collaboratively address bottlenecks in student learning that were impeding a smooth transition from high school to college.

2 Methods

2.1 The Decoding Experience

As a participant in the *Decoding Transitions to College Project*, I engaged in the first several steps of the Decoding process, namely identifying a bottleneck in student learning, elucidating the steps necessary to get past the bottleneck, and creating ways to model these steps for my students. I focused on the bottleneck of successfully answering the population growth assessment question described above. While this was a very specific bottleneck, it served as a proxy for an advanced level of graphical literacy. Therefore, any pedagogical strategies resulting from the Decoding process would target general graphing skills of university students and not one specific assessment question. In Decoding, the steps required to overcome a bottleneck are often revealed through an intensive hour-long interview by two colleagues. During my decoding interview, I was truly shocked by how many steps would be required to correctly answer the assessment question. In the moment, I realized that I was not providing nearly enough preparation or structure for my students to successful interact with graphs. The post-interview process involved reflecting on the interview transcript to pinpoint the specific steps I had discussed to get through the bottleneck. I ultimately identified at least 11 steps necessary to correctly answer the assessment question.

2.2 The Graphing Checklist

Mirroring the steps identified during my interview, I developed a "graphing checklist" that would provide a generalizable and stepwise strategy for interacting with a new graph and its relevant biological context. I was able to categorize these steps into three fundamental skills needed to successfully interact with a graph: ***orientation*** (e. g., identifying independent and dependent variables), ***pattern recognition*** (e. g., describing the shape of the function), and ***interpretation*** (articulating *why* the function was changing in this way and connecting that information to the relevant biological concepts; Table 1). Notably, Pelnar and Cameron (2021), who examined the mental processes used by undergraduate psychology students when interpreting graphs, independently identified the same three categories of processes (orientation, pattern recognition, and interpretation) accomplished by students when encountering a graphical representation of data.

Table 1: Graphing checklist questions, categorized as orientation, pattern recognition, and interpretation. Questions were modified slightly for each checklist to address the relevant components of each graph.

Category	Question
Orientation	What is the independent variable?
	What is the dependent variable(s)?
	What are scale and units on the axes?
Pattern Recognition	What is the shape of the graph(s)?
	If there is more than one graph, what variable does each one represent?
	How is the graph of the dependent variable(s) (y-axis) changing as you increase along the x-axis? Write out this relationship.
Interpretation	Why are the graphs changing in this way?
	Are there any important points to note and how do they relate to the course concepts?
	Have we discussed any graphs related to this one?

2.3 Pre-Course Surveys of Biology L111 Students

2.3.1 Assessing Prior Course Experience

During the first week of the semester and prior to introducing the graphing checklist, I surveyed my students to determine the extent of their mathematics and biology background. The surveys were administered via the Canvas Learning Management System. The students were asked to indicate the highest level of biology completed prior to enrolling in Biology L111. Their options included both secondary school courses (Advanced Placement [AP] or dual-credit Biology, General Biology, Honors Biology, or Honors Biology in 8^{th} grade), university courses (Biology L112 Foundations of Biology: Biological Mechanisms or 200-level Biology or higher), or "other." In addition, the students were asked to indicate their highest level of mathematics prior to enrolling in Biology L111; the options included both secondary school courses (Algebra II, Pre-calculus, Finite Math, Calculus I, Calculus II, AP Calculus AB, AP Calculus BC), university courses (College-level Calculus I, College-level Calculus II, or a more advanced course than university Calculus II), or "other."

2.3.2 Assessing Incoming Graphing Skills

Another key step in the Decoding the Disciplines paradigm is to assess the effectiveness of the intervention. Thus, I evaluated the effectiveness of the graphing checklists using identical pre- and post-semester assessments of students' abilities to successfully answer questions related to graphical orientation, pattern recognition, and interpretation. Scores for orientation, pattern recognition, and interpretation skills were averages of five, six, and five questions, respectively. The questions on these assessments were nearly identical to those in Table 1.

The graphing pre- and post-assessments also asked students to rate their ability to read and interpret graphs at the beginning and end of the semester on a scale of 1 to 5 (ranging from very weak to very strong). Such self-confidence ratings have been shown to be correlated with actual performance, permitting such ratings to serve as a proxy for student metacognition (Kleitman & Stankov, 2007).

2.4 Application of the Checklist

The graphing checklist was implemented during the fall semesters of 2022 and 2023 in Biology L111. In 2022, I taught two sections of L111, with 130 and 220 students, while in 2023, I taught one section of 148 students. During both years, approximately 70 % of these students were in their very first semester of undergraduate education.

Throughout the semester, the graphing checklist was provided whenever a new graph was presented in class. These checklists were embedded in a "note template" that followed along with my slides, allowing students to fill in notes as we progressed through the lecture. A total of 19 checklists, each modified slightly to address the specific graph, were provided throughout the 16-week semester. These graphs provided visual representations of concepts involving population genetics, genetic drift, mutation-selection balance, population growth, and resource competition. They varied from simple to complex graphs, as defined by Glazer (2011). Simple graphs present only one or two variables along two axes (x and y). Graphs of medium complexity may include more than two variables (e. g., the graph of the Hardy-Weinberg principle), and complex graphs can involve interactions between these variables (e. g., reaction norms) (Glazer, 2011).

During class, students were guided through the checklist by following my slides and lecture to ensure that everyone present would have a written record of the correct interpretation of the graph and its relevance to course content. For the first several checklists, I was careful to model in my slides the level of detail required for each question. As the semester progressed, I gradually began to solicit student input during lecture, prompting them to volunteer their interpretations of the graph. This approach allowed me to informally assess whether students were learning to detect and articulate the connection between the patterns depicted in the graph and the biological concept at hand. The students kept their checklists; I did not assess the checklists themselves, as they were meant to be a resource for the students to possess and use in whichever ways they found helpful.

2.5 Mid-Semester Assessments of Perceived Effectiveness of Graphing Checklists

In both years, students were surveyed via an optional Canvas survey (worth 1 point of extra credit) about their perceived usefulness of the checklists. In 2022, the survey was administered during the sixth week of the 16-week semester, while in 2023, the survey was administered during the tenth week of the semester. In both years, students were provided with eight ways in which the checklist could be helpful:

- orienting to only the most challenging graphs in the class
- interpreting and understanding only the most challenging graphs in the class
- orienting to all of the graphs in the class
- interpreting and understanding all of the graphs in the class
- completing homework problem sets
- completing quiz questions
- interpreting graphs in other classes
- interpreting graphs in scientific papers
- I did not find them helpful at all

Students were prompted to check all options that applied to their experience.

3 Results & Discussion

3.1 Prior Course Experience

The variation in preparedness was eye-opening; less than half the students (42 % in 2022 and 46 % in 2023) were adequately prepared for the course, which I consider as having at least taken Advanced Placement or dual-credit Biology in high school. The remainder of students had only taken a general or honors biology course anywhere from 2 to 4 years prior to starting college. Moreover, the first-year students in 2023 likely took their first biology class online, as biology is typically offered during the second year of high school. A higher proportion of students were prepared in terms of background in mathematics, with 82 % of students in both years having completed at least pre-calculus. The incoming biology skill set of Biology L111 was not well aligned with their post-undergraduate goals, with 70 % (2022) and 73 % (2023) of students indicating that they planned to attend either professional (medical, dental, veterinary, or nursing) school or graduate school. Based on my extensive experience working with Indiana high school biology instructors through our university's dual-credit program, such variation in collegiate preparedness is likely related to the socio-economic disparities that exist among high schools in our region. Private high schools and suburban high schools in economically wealthy areas tend to have more resources for teaching staff and are therefore able to offer more advanced science classes. More urban and rural high schools are under-resourced and may only have one course offering each of biology, chemistry, and physics. Such disparities in school funding are compounded by correlations with poverty levels within the community.

3.2 Pre- and Post-Semester Graphing Assessments

In 2022, students exhibited marginal improvements in the questions related to orientation (+3 %) and interpretation (+4 %); however, in 2023, improvements were substantially larger, with increases of 11 % and 12 %, respectively. In 2022, overall scores were significantly higher for the post-assessment (88.3 %) compared to the pre-assessment (85.7 %; paired t-test: $t = -3.57$, $df = 276$, $P < 0.001$), and the improvement was even larger in 2023 (91.5 % versus 83.3 %; $t = -8.47$, $df = 126$, $P < 0.0001$). Scores for questions related to pattern recognition only exhibited marginal changes, if any, between pre- and post-assignments in both years (0 % in 2022 and + 4 % in 2023). Overall, after 16 weeks of class, students exhibited substantial improvement, especially in 2023, in orienting themselves to the variables and axes of the graphs as well as interpreting *why* the data were changing as represented and how to interpret these patterns in terms of course concepts.

The larger improvements in 2023 compared to 2022 may be related to the substantially lower number of students I was teaching in the former ($n = 148$) versus the latter ($n = 350$). In 2023, my teaching efforts were not divided between two large lecture sections. Moreover, in 2023, I purposely reminded students on a regular basis *why* we were using the graphing checklists and how, even if they were doing well in the course, the checklists were helpful for others who might not be so fortunate. In fact, I presented the survey data related to biology background during class, to highlight the variation in preparedness. This effort at student "buy-in" was in response to a substantial proportion of university course evaluation comments in 2022 that indicated that the students found the checklists to be tedious. Many of these students implied that the graphing checklists were "busy work" that was below their skill level. Hence, in 2023, I chose to appeal to their altruism by pointing out the disparities among their peers in preparedness for the course.

The graphing pre- and post-assessment questions that asked students to rate their ability to read and interpret graphs at the beginning and end of the semester revealed several notable results. The students rated themselves on the post-assessment without access to their rating on the pre-assessment. In both years, students varied greatly in how they rated themselves before and after the course (Table 2). In both years, the percentage of students rating themselves as "very strong" increased by the end of the course (by 5 % in 2022 and by 14.1 % in 2023; Table 2). Moreover, 25.7 % of the 2022 students increased their overall rating by the end of the course, while 35.4 % of 2023 students increased their rating. Interestingly, in both years, over 50 % of students did not change their rating, which supports previously reported correlations between ratings and performance (Kleitman & Stankov, 2007).

Table 2: Percentages of students rating their "ability to read and intepret graphs" on a scale of 1 to 5 on the pre- and post-semester graphing assessment. Ratings were 1 (very weak), 2 (moderately weak), 3 (moderate), 4 (somewhat strong), 5 (very strong). Included are data for the number of students for whom I have scores for both assessments in each year as well as the percentage of students whose scores increased, decreased, or did not change from the pre-semester to the post-semester assessment.

	2022		2023	
	Pre-assessment percentage	**Post-assessment percentage**	**Pre-assessment percentage**	**Post-assessment percentage**
Rating				
1	0.4	0.7	0	0
2	2.9	5.1	7.1	3.1
3	27.9	25	29.9	26.8
4	51.1	46.4	48	40.9
5	17.8	22.8	15	29.1
Changes in ratings				
Number of students		276		127
Increased (%)		25.7		35.4
Decreased (%)		23.2		13.4
Did not change (%)		51.1		51.2

Many students who rated themselves highly along this scale in the post-assessment cited the graphing checklists as having helped to improve their abilities to understand and interpret graphs. For example, in 2022, a student who increased their rating from 3 to 4 reported:

> *"After this class, I definitely feel more confident in reading graphs and being able to explain them to someone else. I think the graphing checklists helped me a ton and I really appreciate them."*

Similarly, in 2023, a student who increased their rating from 4 to 5 stated:

> *"After using graphs throughout the entire semester in this class I feel it has really strengthened my ability to read and interpret graphs in a way I can correlate* [sic] *to my other classes. I think what helped me the most was the graphing checklists as it forced me to really think through what the graphs were saying and how to interpret them."*

Interestingly, in 2022, a student who decreased their rating from 3 to 2 said this at the end of the course:

> *"I thought I was decent at interpreting graphs until I took this class. There's a lot that goes into interpreting graphs and histograms."*

3.3 Mid-Semester Assessments of the Effectiveness of Graphing Checklists

In 2022, 78.5 % of all students who completed the mid-semester survey (n = 297) found the checklists helpful for at least one of the eight possible ways listed in the "Methods." For example, 42 % of students found the checklists helpful in completing homework assignments, and 38 % found the checklist helpful in answering quiz questions. In 2023, this survey was administered later in the semester, and results indicated that 93.9 % of all students surveyed (n = 115) found the checklists helpful. This group of students found the checklist most helpful for completing for interpreting and understanding all graphs in the class (31 % of respondents), while 27 % found them helpful for interpreting and understanding only the most challenging graphs in class. Similar to the graphing assessment scores described above, the increase in overall perceived utility of the checklists in 2023 (93.9 % versus 78.5 %) may be due in part to the student "buy-in" effort and the fact that the 2023 students had an additional 4 weeks of checklists by the time they were surveyed compared to the 2022 students.

3.4 Other Indicators

As described earlier, universities often use DFW rates as a metric of student success in a given course. High rates are generally viewed as problematic in terms of instructor grading or a mismatch in the level (100, 200, 300, or 400) of the course and difficulty of course content. In 2022, my two sections of L111 exhibited a lower DFW rate (21.9 %) compared to 2021 (22.3 %). The DFW rate dropped even further for my section in 2023 (16.4 %).

In terms of the exam question that inspired the use of Decoding the Disciplines to dissect the steps required to answer the question correctly, student performance increased from 40 % in 2021 to 48 % in 2022. In 2023, the question was modified to be even more challenging (i. e., the question had more than one correct answer), yet 43 % of students were able to answer it correctly.

4 Conclusions

In his review of the literature on the interpretation of graphs, Glazer (2011) emphasizes the need for explicit instruction on interpreting graphs in introductory university science classes as well as research that monitors the effectiveness of specific interventions to improve graphing skills. The present study achieves both goals.

A substantial proportion of my Biology L111 students completed my class with enhanced abilities to read and interpret visual representations of course concepts. Needless to say, implementation of the graphing checklists was not the only variable that changed among years; thus, one can only point to a potential correlation (versus a causative relationship) between the use of the checklist and graphing assessment scores, student self-ratings, course DFW rates, and exam performance on graphing questions. That said, as long as students continue to self-report that the graphing checklists are directly related to their perceived improvements, I will consider the approach a success.

The present work provides a tangible and valuable example of the power of the Decoding the Disciplines paradigm. A direct line can be drawn from decoding the bottleneck of students' ability to interpret graphs to quantifiable improvements in student success in this introductory biology course. Student populations in both years were comprised of approximately 70 % first-year students who varied widely in their level of preparation for college-level biology. One can say with reasonable confidence that by the end of the course, those gaps had been at least marginally closed, thereby aiding in the transition of these students from high school to university. Individuals and groups using Decoding the Disciplines continue to successfully translate its power into concrete methods for enhancing students' higher-level learning.

Notes

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Using *Decoding the Disciplines* to Elucidate the Mental Processes Involved in Reading Graphical Data

E. Leslie Cameron, Kari L. Duffy

Summary

A goal of many undergraduate majors is to improve quantitative literacy. This paper addresses one aspect of quantitative literacy, namely the reading of graphical data. Using the *Decoding the Disciplines* approach, we have identified graph reading as a *bottleneck* and engaged three faculty in *decoding* interviews. The interviews revealed these mental moves in graph reading: establishing a context or orienting to the graph (including understanding the axes), looking for a *pattern* in the data and generating a verbal statement about the relationship between variables. We found that graph reading is an iterative rather than a linear process. Moreover, there was a consensus among the interviewees that faculty make assumptions about students' ability to understand graphical data and that many students have not been taught, at least explicitly, how to read a scientific graph as scientists read them.

Keywords: Quantitative Literacy; Graph; Decoding the Disciplines; Bottleneck

Die Anwendung von *Decoding the Disciplines* zur Verdeutlichung der mentalen Prozesse beim Lesen grafisch visualisierter Daten

Zusammenfassung

Ein Ziel vieler Studiengänge ist es, die Kompetenz zu verbessern, quantitative Daten zu verarbeiten und interpretieren. Dieser Beitrag befasst sich mit einem Aspekt dieser Datenkompetenz, nämlich dem Lesen grafischer Darstellungen. Mit Hilfe des Decoding the Disciplines-Ansatzes haben wir das Lesen von Grafiken als Engpass identifiziert und drei Lehrkräfte in Interviews befragt. Die Interviews ergaben folgende mentale Schritte beim Lesen von Diagrammen: Herstellen eines Kontextes oder Orientieren am Diagramm (einschließlich Verstehen der Achsen), Suchen nach einem Muster in den Daten und Erstellen einer verbalen Aussage über die Beziehung zwischen Variablen. Wir haben festgestellt, dass das Lesen von Diagrammen eher ein iterativer als ein linearer Prozess ist. Darüber hinaus waren sich die Befragten einig, dass die Lehrkräfte Annahmen über die Fähigkeit der Studierenden treffen, grafische Daten zu verstehen, und dass vielen Studierenden nicht – zumindest nicht explizit – beigebracht wurde, wie wissenschaftliche Grafiken zu lesen sind bzw. wie Wissenschaftler:innen sie lesen.

Schlüsselwörter: Quantitative Datenkompetenz; Diagramme; Decoding the Disciplines; Lernhürden; Statistik

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1 Introduction

A goal of many undergraduate programs, particularly in the social and natural sciences, is to improve students' quantitative literacy skills. One aspect of quantitative literacy that is particularly important to students' success is their ability to read[1] graphical data. In psychological science, there is an ever-increasing emphasis on methods and statistics, even at the very early stages of undergraduate education in the United States. The American Psychological Association (2023) explicitly states that the interpretation and communication of graphical data should be a goal of undergraduate psychology education. Reading graphs, the topic of the current study, is a skill needed by students in many disciplines in addition to psychology. Graph literacy is defined as the "ability to understand graphically presented information and includes general knowledge about making inferences from different graphic formats" (Okan et al., 2016, p. 271). If it is low, it leaves one susceptible to accepting misinformation. Thus, the interpretation of graphical data and quantitative literacy, generally, is important for informed citizens.

Many students struggle with graph literacy (for a review, see Glazer, 2011). We have also observed that many psychology students struggle to communicate clearly about data, which in some cases is a failure to understand data. We have observed this in students' oral presentations of empirical findings presented graphically (Cameron & Duffy, 2015). Specifically, when presenting data orally, students often did not identify what had been manipulated and measured (i. e., describe axis label), nor did they describe important differences between conditions (i. e., describe *trends* in the data), consistent with the findings of Picone et al. (2007). In a lab setting, in which students and faculty read graphs while their eye movements were monitored, students often failed to *describe* graphs and jumped quickly to attempting to state conclusions without carefully examining the data (Pelnar, 2019; Robbins et al., 2019). Moreover, in that study, overall performance on graph reading was lower in students than faculty and the faculty spent more time looking at parts of the graph that provide important information for reading the graph. These findings are in accord with other findings in the literature that have reported that eye movements when viewing graphical data depend upon scientific expertise (e. g., Harsh et al., 2019). Interestingly, students do not always demonstrate awareness of their lack of understanding (Cameron et al., 2016), a general feature of metacognition that has been described in a variety of contexts (e. g., Kruger & Dunning, 1999).

The ultimate goal of our work is to help undergraduate students understand and communicate more clearly about graphical data. We find this to be a struggle that exists in our students, despite the fact that, anecdotally, students indicate that they began encountering graphical data in elementary school and teaching about graphs and tables is part of primary and secondary curricula in the United States (Friel et al., 2001; Zucker et al., 2015). Glazer (2011) argued that graph reading competence should be explicitly taught given its importance and its complexity, but noted that few scholarly articles were available on explicit educational pedagogical practices at that time. Life science faculty endorse the importance of teaching science skills at the college level, including interpreting graphical data (Coil et al., 2010) and some methods have been suggested for teaching these skills at the college-level (e. g., Harsh & Schmidt-Harsh, 2016; Picone et al., 2007) and pre-college (Zucker et al., 2015).

In order to develop a systematic approach to teaching graph reading in post-secondary education, we have taken a *Decoding the Disciplines* approach to, first, identify the steps experts take when reading graphs (the primary focus of the current paper) and second, to develop teaching tools. The *Decoding* approach is distinct from verbal protocol procedures such as think-aloud (Trickett & Trafton, 2007), which does not involve asking participants *what* and *why* particular mental processes are at play.

1 We use the word "read" graphs because it seems to be the most encompassing term for this activity, which includes looking at a graph, interpreting and describing it. Our understanding of the processes changed through these interviews and hence we have needed to modify our word-choice accordingly. For example, we originally used the word "interpretation", which we discovered really seems to refer to a very high-level mental process and the bottleneck we face with our students is much more fundamental than that. Students have difficulty even describing graphical data. We describe the evolution of terminology in the Results section, under "Decoding the Disciplines Step 1: The Bottleneck."

Decoding has begun to be applied in the teaching of psychology, particularly in research methods and scientific thinking (Bihun & Handelsman, 2018; Pinnow, 2016). Decoding has been described as part of the "second wave of SoTL" (Gurung & Schwartz, 2010) as it provides a mechanism for studying learning within a discipline.

The current work revolves around *Decoding* interviews (Step 2 in *Decoding*), which start with articulating a bottleneck. The current bottleneck evolved throughout the course of this work, as described below. Articulating the bottleneck and describing the mental moves used by faculty in the task at hand is central to *Decoding* but is sometimes difficult because the expert unconscious mental processes have become so automated. Many experts find it challenging to articulate their mental processes and some even experience frustration or resistance to the process (Pace, 2017). The problem is akin to the *curse of knowledge* (e. g., Camerer et al., 1989), which can make teaching difficult (Bransford et al., 2000, cited in Pace, 2017).

The goal of this project is to apply *Decoding* to clarify the steps used by faculty who are proficient at interpreting and communicating about graphical data. We describe *decoding* interviews with faculty who have agreed that, generally speaking, reading graphical data is a bottleneck for the undergraduate students they teach. These interviews, which are available on OSF[2], reflected the difficulty in making explicit the implicit steps involved in a task that is routinely performed by faculty in the social and natural sciences. However, the interviews revealed a set of mental operations that faculty go through as they read graphs and also reinforced the fact that being able to read a graph is not the same as consciously knowing how one does it. Armed with the knowledge of *how* one reads a graph should allow faculty to teach these steps to students to improve their ability to read and describe graphical data.

2 Method

2.1 Decoding Interviews

We conducted three interviews in which we asked undergraduate-level teaching faculty to make *explicit* their *implicit* mental processes as they interpret graphical information. The Carthage College Institutional Review Board approved this study and participants gave their informed consent.

In Interview #1, the first author (LC, a psychologist) and a physicist (PR) were interviewed by the second author (KD, a communications professor) and a historian (DP), experienced in *Decoding*. This interview took place at the European Scholarship of Teaching and Learning Conference in Lund, Sweden, after LC and PR attended a pre-conference workshop on *Decoding* and requested that the workshop leader (DP) conduct an interview to decode their mental processes as they read graphs, which they had discovered was a shared *bottleneck* in their students' learning.

The second two interviews were conducted by the authors of this paper. The interviewees were selected because they had participated in the related pilot experiment in which their eye movements were tracked while they read and described a set of graphs (Cameron, 2019; Pelnar, 2019; Robbins et al., 2019). The descriptions of graphs by these two faculty were excellent and thus they were considered to be very proficient graph readers.

In Interview #2, the interviewee was a recently-retired male faculty member from the Chemistry Department at Carthage College. In Interview #3, the interviewee was a mid-career female faculty member from the Environmental Science Program at Carthage College. Interviews lasted about an hour each.

At the start of each interview, the *decoding* paradigm and the goal of the interview were briefly described. The interviewees confirmed that the ability to read graphs is a *bottleneck* for students in their science classes. In these semi-structured interviews, the interviewer was an active participant.

2 https://osf.io/3ntqv/?view_only=f22ca25098c54507919954fa0b699f3d

They asked open-ended questions to encourage the interviewee to articulate their implicit mental processing. When appropriate, they sought clarification and asked follow-up questions. The goal of these interviews was to uncover underlying mental processes involved in disciplinary thinking.

2.2 Data Analysis

Interviews were transcribed by an undergraduate research assistant and checked for accuracy by the authors and another undergraduate researcher. Then, each interview was scrutinized to confirm the bottleneck and to extract the main steps to graphical interpretation that were articulated by the interviewee. These articulated steps were confirmed by trained undergraduate researchers. Finally, we developed a more thorough set of steps in graph reading that could be used to create exercises to teach to students, given that moving beyond the bottleneck will help students understand, consume and communicate more clearly about data.

3 Results

3.1 Decoding the Disciplines Step 1: The Bottleneck

The first part of each *decoding* interview involved the interviewee clearly articulating the *bottleneck* they had identified.

The precise articulation of the bottleneck identified here, with respect to graph literacy, evolved over the course of this project. Given that the evolution of the bottleneck illustrates how our thinking about the problem became more nuanced and clarified our understanding of what needs to be taught, we describe that evolution here in some detail.

We came to the first interview with the idea that our (LC and PR) shared bottleneck was about "data interpretation." One of the interviewers (KD) summarized the bottleneck early on in that interview by saying "You're having a hard time... *teaching* students how to *interpret* the data." While we agreed with this articulation, PR indicated something that we both agreed upon, "I've never taught them!" he said. This theme, interestingly, emerged in all interviews. There was agreement that graph reading is not a skill that we explicitly teach, and, in fact, we often make assumptions about what students know. Yet, we all agreed that graph reading is a critically important skill. Moreover, LC indicated several times in the original interview that the fundamental bottleneck was really in the *description* of data. At the start of the interview, she described the problem this way:

> So, I'll give an example from when I first got started with this [working with students on communicating about data] which was having students do online laboratories, where, outside of class, they were doing a cognitive task on a computer that collected data and the online program then provided them with a graphical representation of the data from all the students in the class. Their assignment was to both write about the data and speak in class – present to their peers – an analysis of the data. Only the graph, nothing statistical. Simply, "here's a graph and here's a representation of the data we collected". And it seemed to me that **students had a hard time describing those data to me and to their peers, and also had a difficult time writing about it** ... and it seemed to me that they often missed steps. **There would be simple things they didn't do to help orient people to the graph and to the axes and to what they were actually showing.** So, they acted, sometimes, so as though it was sort of self-evident and they would blow right through, **without giving a clear description**. So, for me that was the starting point. [Emphasis added.]

In fact, in all interviews, faculty indicated that if we could help students improve the simple *description* of data, we would feel that we had made progress. The *interpretation* of data was only a consideration after the basic graphical information had been understood. For example, LC responded to PR's description of a bottleneck and made a distinction between *interpretation* and *description* of data:

> I actually heard three things in there. One had to do with an **expectation** of what the data will look like, in other words a **hypothesis**, a prediction of what might happen. There was clarity in **describing** the data, and then there was **interpretation** of the data. **And I think I was starting with just "Could we get a de-**

> **scription of the data?."** A clear description of the data, maybe even before the hypothesis and the interpretation. [Emphasis added.]

In terms of articulating more precisely the problem that students have, in her interview, LC indicated that she thought students miss many of the critical foundational steps to understanding graphical data. After describing how she believes that she works through trying to make sense of the axes on a graph, which was what she thought was her first step, LC said:

> … what I was finding with students is that they were skipping everything that we've just described. Right? They don't tell you what's on the axes. And then they move directly to what I would say, now, after having done all that work, the meat of the matter which is: is there a difference? Which is a statistical question. But they've moved entirely beyond that without doing this other more basic work.

In the course of the interview, LC realized that the bottleneck was perhaps more basic than the "interpretation" of graphical data:

> … now this has helped me clarify that the problem, I don't even want them [the students] to go yet to the problem of whether or not there's something important**… I just want them to describe what is there**…. And if I got there, I think I would be really quite happy.

Likewise, PR indicated "I feel like it [the graph] has not been described by the students." LC responded to PR saying "That's exactly right, and they speak as though it's self-evident" and continued later to say "And, again, they do this thing where they start, you know, three-quarters of the way into the explanation as opposed to stepping back [i. e., to provide a basic description of the axes]."

Further, DP (interviewer) suggested that "They can see the number but they can't read the axis because they aren't doing the things that you just did" and that "students tend to want to do things too fast." LC responded that when that happens:

> … I'm frustrated because I feel that they've missed that, they've gone right to the meat and they're not able to really understand the meat because they didn't understand the foundation.

The articulation of the bottleneck that was provided to the interviewees in Interviews 2 and 3 evolved slightly. To TE, the interviewer LC described the bottleneck this way: "they [students] have difficulty reading graphs, not even necessarily talking about interpreting, but even describing what's there and maybe understanding where the data come from." To SR, she said that the bottleneck involved: "… reading, kind of interpreting and reading graphical data and communicating clearly about those graphical data."

At the end of Interview 3 with SR, LC (as interviewer) says:

> And I do think there is some agreement that that's what we want students definitely to be able to do because the interpretation is about the discipline and it's not necessarily what they need carrying forward, right? That they can do the former. Then it doesn't matter what context they're in, they will have that skill. That is the bottleneck, right? So, the bottleneck is the description and not so much the interpretation, at least in my mind, I've changed from thinking it was interpretation to thinking, "no, it's really what I was calling 'description' of the data."

3.2 Decoding the Disciplines Step 2: The Interviews

3.2.1 Steps to Graphical Interpretation

An analysis of the transcripts led to the following summaries of steps that each faculty described that they take as they read graphical data. It is important to note that although there are some discrete steps in graph reading, the faculty all described a process that is iterative and not linear. It is worth highlighting that the interviews lasted about an hour to describe a process that happens in seconds.

That is, graph reading is so automatic for faculty experts, and we were not aware of all of the steps that we make effortlessly. The fact that it might help our students if we were more explicit about these steps became increasingly clear as *decoding* took place. For example, during the interviews, we noticed some of the assumptions of student understanding that we take for granted may not be warranted, at least not for all students.

LC (Psychological Science)

1. "...start with... what are the axes?"
   a. *Look at the y-axis, in particular the labels, and consider what is being measured (i. e., the dependent variable)*. In the interview it became clear that an understanding of the dependent variable relies on some prior knowledge, which may include the experimental method used to collect the data and an understanding of what the numbers represent. DP accurately reflected back "So there's a story behind the y axis."
   Further, LC indicated that interpretation of the data would include consideration as to whether or not the data were "within the realm of possibility" or met some expectation. Were they reasonable (e. g., were there measurement errors)? Also, implicit in this analysis is a consideration of variability and inherent noise in the data.
   b. *Look at the x-axis and consider what is being manipulated (i. e., the independent variable)*. In this step, the type of graph (e. g., line, bar, scatterplot, etc.) is important to understand how many independent variables and conditions of the independent variable(s) there were in the study. Again, there was a need to refer back to the experimental method to understand the manipulations.
2. *Look for the pattern in the data*. In this step, LC discussed looking for *differences* between data points, such as the *difference* in height between two bars on a bar graph (perhaps the simplest comparison to make). This step is important because students often seem to get caught up describing extraneous details about the data (e. g., specific data points) and miss the relationship among the data points.
3. *Consider statistical differences, meaningful differences and confounding variables*. Once the pattern of the data is understood then whether that pattern is statistically significant is an important step in reading a graph. Although this is critical scientific data analysis, it is a step beyond the bottleneck of interest and the focus of the current study, which is a clear description of data.

TE (Chemistry)

1. *Look at the title and the "figure caption"*[3]. TE described first looking for *words* in the graph. For example, he indicated that he looks for words like "reaction rate" and perhaps some other information like units or how measurement happened. TE described *preparing the foundation* or *doing the groundwork* before even looking at data. He talked about establishing the *big picture* and recalling deductions he had made before. As in the interview with LC, TE used the phrase "back and forth" or doing "more than one read", indicating that graph reading is not a linear process.

3 TE actually used the word "legend." During the interview, we understood him to mean "figure caption." We confirmed, after the interview, that we had correctly understood him.

2. *Look at the y-axis*. TE said at this point he would be looking for whether the numbers were increasing or decreasing because "I have already absorbed the *words* associated with the axes." He indicated that he would look at whether the axis is linear/logarithmic or exponential.
3. *Look at the trend(s)/pattern(s) in the data*. When TE got to the data themselves he immediately described looking for the **trend(s)**. He talked about trying to *describe* the **pattern** in his mind or in writing.
4. *Interpret the data*. The final step described was the interpretation of data. In the interview this occurred very quickly at the end and seemed of secondary importance. The vast majority of time in the interview was focused on getting to a clear *description* of data, which TE considered the most important skill for students to develop.

SR (Environmental Science)

1. *Look at the y-axis*. SR indicated that she "look[s] at the y-axis first because that's typically the dependent axis and that's usually what it is that we're measuring and that feels more fundamental to me." SR pointed out that you can use the axes to find variables, and she teaches her students to do that.
2. *Look at the x-axis*. SR indicated that "So the next question is, "OK so what's, you know, causing that to vary? What's the other variable that we are comparing that to?" And again, that would typically be on the *x-axis*."
3. *Look at the data/pattern/trend*. In her words,

   > So, once I know what I'm comparing, the next step is actually to look at the data itself. In other words, I think I would then go from the axes to the actual graph, and that the first thing I'm looking for is a pattern ... there's probably a hidden step in there, which is, a pattern looks different for different graph types. So, there's a part of my brain, I think I'm not catching that is distinguishing which is which. But I think the next step would be to sort of look at the pattern or the trend. Is this, you know, is it increasing? Is it decreasing? .... does it fit my mental image of what's (right), so you know, a simple one would be "is it increasing over time?" Is it – you know, you could say that's [a] positive slope or, that's something I could draw with my hands. If there is a trend line, look at that and not at individual points.

   SR also noted, when thinking about details in the graph later: "The story is not about whether the concentration is 200 or 400. The story is the trend, right, the story is that this is increasing over time." Further she indicated that "I think some of the times I actually formulate a sentence like that. You know, the y depends on x."
4. *Iterate on the axes*. SR described coming back to look at the details of the axes for the scale, for example. She indicated that she would look at the title and figure captions last. She also indicated that perhaps she would look at outliers to see if it is an error, random or something meaningful.
5. *Consider statistical significance*. SR indicated that the last thing she would look at would be error bars and statistics.

3.2.2 Synthesis of Interviews

There was remarkable similarity in the series of steps of graph reading that these three faculty members, from different disciplines, described. All three described looking at the y- then x-axis and that orienting themselves to the graph was a critical first step. They then looked at the *pattern* of the data as opposed to getting caught up in individual data points. Coming to an understanding of the pattern of the data made up the bulk of the mental work that the faculty described. Moreover, the pattern of the data was considered by all three to be much more fundamental and important in teaching than considerations about statistical significance and interpretation or putting the data into the broader context of the scientific literature. That is not to say that interpretation is not essential, but interpretation is impossible if there is not an understanding of the data. Moreover, there was an appreciation for the fact that the ability to interpret data depends upon some prior knowledge. We (faculty) approach graphs with some expectations of what they might be like and what is in the realm of possibility. SR suggested that perhaps we are comparing the graph to a template, like a "filter" (e. g., "it's positive, it's negative, there's no relationship") and also indicated that we probably have expectations for any type of plot, regardless of the topic of the graph. Again, there is likely important work to be done to fully appreciate faculty's ability to interpret data and there is, undoubtedly, deep knowledge about data and disciplinary-specific knowledge that come into play in those mental processes. Future research in decoding in that domain could be illuminating.

The steps faculty described in graph reading are represented in Figure 1. The figure highlights the fact that the process is not linear but rather involves iterating on the steps to deepen an understanding of the data. The red lines in the figure represent the initial flow of processing described, and the blue indicate that the faculty described returned to previous steps as they worked towards an understanding of the data.

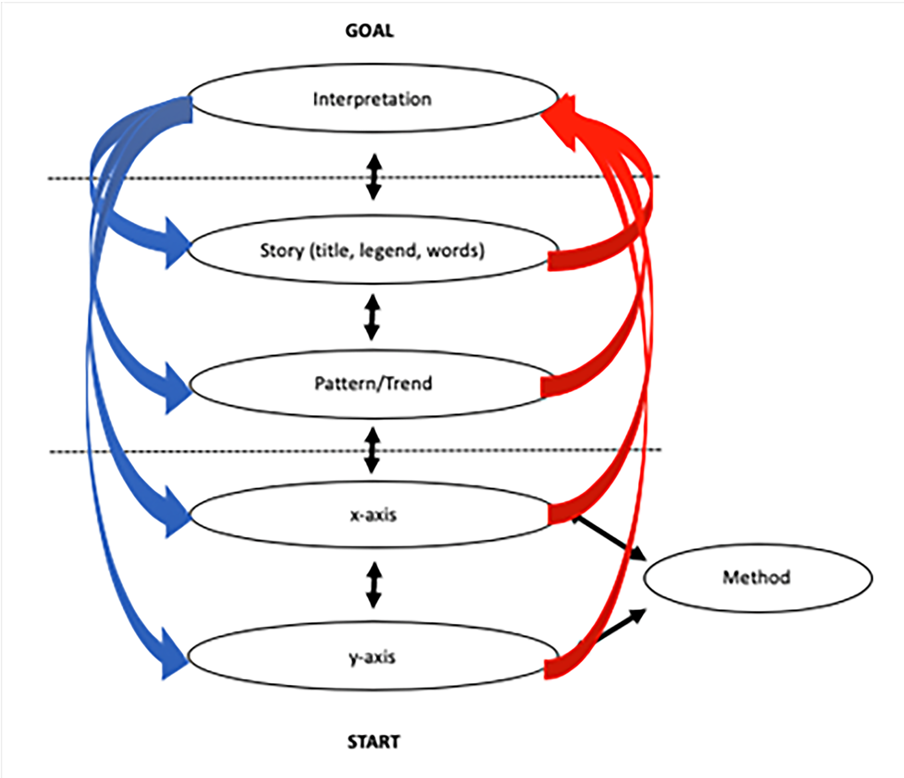

Figure 1: Graphical Representation of the Steps Taken by Faculty in Reading Graphs Note. The arrows are meant to demonstrate the iterative, non-linear nature of the graph-reading process

4 Discussion

The *decoding* interviews revealed remarkable similarities in the steps that three faculty members from diverse disciplines take in reading graphs. The interviews also uncovered a number of aspects of graph-reading that may contribute to the challenges that students face in communicating clearly about them. This work has made clear to us that the problem we face in teaching students to communicate more clearly about graphical data stems from the challenge they face in providing a basic description of the data even before more complex interpretation. This point was made clear from the evolution of our bottleneck.

The faculty interviews revealed that orienting to the graph (i. e., looking at axes and identifying variables) is an important first step to reading a graph. This is consistent with the literature on experts and problem solving, which shows that experts get off to a slow start in problem solving because they take the time to orient themselves and figure out how best to set up the problem (e. g., Lesgold, 1988). Interviewee TE (#2) described this as *preparing the foundation* or *doing the groundwork*. Much of the *decoding* interview with interviewee LC (#1) also revolved around gathering the information necessary to understand the y-axis. Given the consensus among the faculty interviewees, it is worth explicitly *teaching* this step to students.

This mental work is important both for reading a graph and communicating clearly about the data depicted in a graph. We have observed students describe graphical data without providing information that orients their audience to the data (Cameron & Duffy, 2015). Anecdotally, we have observed that scientists and teachers sometimes do the same thing. This is, in fact, at the core of the bottleneck that we wanted to address in our work. Sometimes the lack of important information provided may be the result of the "curse of knowledge" – the speaker has simply forgotten that not everyone is familiar with the data they are presenting – but it is a habit that often reduces the clarity of the presentation of data. Developing this skill in students would certainly help them communicate more clearly and, in fact, may assist with their comprehension of data. This point is related to the issue that students sometimes seem to think that results, such as those presented in graphical form, are "self-evident." While a picture may be worth a thousand words, it is sometimes necessary to use plenty of words to fully describe graphical data.

At the core of the bottleneck of interest in the current study, clarity in describing the graphical data is essential. Clarity requires an understanding of where the data came from, or, in other words, the methods that were used to generate the data. Moreover, clarity requires a description of *differences* or *patterns* in the data. It is important not to "get caught in the weeds." As SR indicated "They [students] always grab – and I've seen it too – where they grab the outliers first." The faculty members were in agreement that if students could successfully *describe* the pattern in the data, that would be a significant achievement and a move past the bottleneck.

The final stages of graph reading include an *interpretation* of the data, including how they fit within a broader context, and an assessment of the *significance* of the data (statistically and in terms of meaningfulness). This requires an understanding of statistical concepts, such as variance and the consideration of confounding variables. These final two steps require a level of analysis that is quite sophisticated and students might struggle with these steps. As noted above, they are issues that go beyond the bottleneck of interest here. That is not to say that the interpretation of data and a deep understanding of statistics is not important. Rather, that discussions of those important concepts may be lost on students if they have not mastered the more basic understanding and ability to describe graphical data.

The interpretation of graphical data is probably more difficult if the reader has no expectation of what the data *should* look like, or, at least, what is in the realm of possibility. For example, it is helpful to know what range of values one might expect to see represented in a graph of manual reaction times. Depending on the context (for example, for data that the student has collected), it might be important to scrutinize the data to see if something is amiss in the data (e. g., an error was made in measurement) or whether there is a pattern of results that might require some explanation (e. g., there is an unexpected finding). For this reason, perhaps we should not expect undergraduate students, with limited disciplinary knowledge, to recognize unexpected results. So, there is orienting to the graph and mathematical possibilities and then also content-specific knowledge that sets one up for a different sort of processing. Indeed, as Harsh et al. (2019) indicated, "a large body of research demonstrates that the ability to make sense of and use graph data and learn interpretive skills is strongly influenced by one's prior knowledge and experience with the content/context of the graph" (p. 2). As SR indicated, faculty do "a little bit different kind of prioritizing that comes from content knowledge." Moreover, SR indicated that "when I see a really regular pattern in environmental data, I'm thinking *something has to be going on there* because a lot of our data isn't regular." For example, she described an occasion in which she figured out that there was a regular pattern to data that was not an artifact and said "… when I first saw what it meant, I just thought: *This is interesting. This seems important.* And then

I'm going to come back later and try to figure out what's happening and why." Noting what is interesting or important requires some disciplinary knowledge, which could be the topic of further research. Asking undergraduates to interpret data is inappropriate if they don't have the relevant disciplinary knowledge.

Increased disciplinary knowledge is probably essential for a complete understanding of data. But in terms of graph reading per se, there are hidden mental processes, such as considering the *method* by which the data were collected that seem to occur in proficient graph-readers and that could be taught. Recently we have conducted similar *decoding* interviews with students, also published in this volume (Pelnar & Cameron, 2025). We have found that students are much less consistent in the steps they describe using when reading graphs and they sometimes underestimate the level of cognitive effort required. Note that in that study, we did not examine how well students could describe graphical data, but rather what steps they thought they used in order to read the graphical data. We (e. g., Cameron & Duffy, 2015) and others (e. g., Darcy, 2025, also published in this volume) have shown the difficulties that students have in reading and communicating about graphical data.

Helping students communicate clearly could be aided by articulating and modeling the series of steps faculty use in reading graphs. Students might be well-served by faculty explicitly describing the mental work involved in, for example, going back and forth between data and method and demonstrating that graph-reading does not occur effortlessly. Faculty also benefit from *Decoding* as it can help them overcome the *curse of knowledge*, reminding them of their own invisible disciplinary thinking. The goal of *Decoding* is to teach students to move quickly through this step to be able to do more advanced disciplinary thinking. In other words, the ability to "read" a graph is a bottleneck that, when overcome, will help improve students' understanding of their discipline.

In this study we have uncovered the way that three faculty experts read graphical data. Although there were remarkable similarities and the series of steps were broadly consistent with those that have been described for pre-college instructors (Zucker et al., 2015), there are likely multiple routes to understanding graphical data. Moreover, some graphs are more complicated than others and may require additional processing.

We encourage faculty, whose disciplines rely on an understanding of graphical data, to consider whether the steps described here might be useful to them in explicitly teaching students how to understand and talk about graphical data. Perhaps even better, we encourage others to undergo a decoding interview to uncover the mental moves they make in reading graphs.

In this paper we have focused on the first two steps of the decoding process (identifying a bottleneck and conducting decoding interviews to make explicit the implicit steps faculty use in completing a task). The next several steps in *Decoding* with respect to reading graphs involve modeling the steps faculty take when they read graphs and teaching them to students. We are currently exploring the effectiveness of modeling the steps of graph-reading that we have described to students and providing them with opportunities to practice using those steps themselves.

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Using Decoding the Disciplines and Students as Partners to Explore Student Graph Reading

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Abstract

In this study, we employed two disparate approaches – Students as Partners (SaP) and Decoding the Disciplines (DtD) – to deepen our understanding of how undergraduate students read graphs. Engaging SaP means including student investigators as equal contributors in a collaborative research project. DtD involves interviewing faculty members to uncover the implicit mental processes that they utilize when doing critical disciplinary thinking. Specifically, our (a faculty and student team) goal was to adapt DtD for use by student interviewers with student interviewees. We describe the steps students report that they take in graph reading, which has been identified as a “bottleneck.” Many students indicated that they think of graphs as self-explanatory images and that reading them is not a process. We contrast these steps with those that have been described by faculty. This project demonstrated that both SaP and DtD are powerful approaches for exploring mental processes in non-experts.

Keywords: Graph literacy; quantitative literacy; visual data; graphical interpretation, Decoding the Disciplines

Wie entschlüsseln Studierende Diagramme? Das Potenzial von Decoding the Disciplines und Student as Partners für die Erforschung von Datenkompetenz

Zusammenfassung

In dieser Studie wurden die Ansätze Decoding the Disciplines (DtD) und Students as Partners (SaP) kombiniert, um die Herangehensweise von Studierenden beim Entschlüsseln von Diagrammen zu untersuchen. SaP integriert Studierende als gleichberechtigte Partner in die Forschung, während DtD die impliziten mentalen Prozesse von Expert:innen offenlegt. Ziel war es, DtD für studentische Interviewer:innen mit studentischen Befragten anzupassen. Die Studie identifizierte Schritte, die Studierende beim Lesen von Diagrammen durchführen, und stellte fest, dass viele Diagramme als selbsterklärend wahrgenommen werden. Diese Ergebnisse wurden den von Lehrkräften beschriebenen Prozessen gegenübergestellt. Das Projekt zeigte, dass SaP und DtD wirksame Methoden sind, um mentale Prozesse beim Lernen besser zu verstehen.

Schlüsselwörter: Datenkompetenz; visuelle Daten; Diagramminterpretation, Decoding the Disciplines

1 Introduction

Quantitative literacy is a crucial skill for success in many undergraduate programs and is important for the general population. In a world where individuals have nearly unlimited access to data, it becomes even more crucial to understand how to read and interpret graphs, lest one be misinformed by poorly designed graphical displays (Cooper et al., 2003; Woller-Carter et al., 2012). In the field of psychology, the American Psychological Association's (APA) published learning objectives include that psychology undergraduate students should be able to 'interpret complex statistical findings and graphs in the context of their level of statistical significance, including the influence of effect size, and explain these findings using common language' (APA, 2013, p. 21). In the current study, we are particularly interested in graphical literacy, which is the 'ability to understand graphically presented information and includes general knowledge about making inferences from different graphic formats' (Okan et al., 2016, p. 271). There is both anecdotal and empirical evidence that students experience difficulty in interpreting quantitative data (Cameron, 2019; Cameron & Duffy, 2025; Guthrie et al., 1993; Kilic et al., 2012; Robbins et al., 2019). In a systematic analysis recently conducted within our institution's psychology department, 91 cases of student-written responses to an in-class task were examined (Bousson, 2024). In this task, students were instructed to describe a graph with which they were presented. These graphical descriptions were then categorized by errors made, which included omitting relevant variables/introducing unrelated variables, misrepresenting variables, making unwarrented causal/inferential claims, and misinterpreting results. By contrast, faculty in psychological science and many other disciplines are highly proficient in reading graphical data. As in other domains, these faculty experts are likely to approach problems differently than novices in their discipline (Chi et al., 1982).

The primary objective of this project was to explore how students approach reading graphs using disparate approaches, with the ultimate goal of helping them communicate more clearly about the data presented in graphs. We will start by describing several approaches we have used in the past as well as ones that we have adapted in the current study.

1.1 Eye-Tracking

One way in which processing graphical data has been examined is through eye-tracking. This is typically used in a laboratory setting with sophisticated instrumentation that can precisely monitor the position of the eye in real time. Position of the eye is thought to be a proxy for underlying perceptual and cognitive processing, and the assumption is that cognitive processes are associated with eye movements because what is seen is rapidly processed at both perceptual and cognitive levels (Emhardt et al., 2020). In our context, this approach is important because several studies have successfully determined what people focus on while reading graphs and found that their eye movements tend to correspond with their descriptions of the data (Carpenter & Shah, 1998; Okan et al., 2016; Ratwani et al., 2008; Sullivan et al., 2011; Woller-Carter et al., 2012).

In a pilot study in our lab, we tracked faculty and students' eye movements with an EyeLink Portable Duo eye-tracking system as they described and interpreted graphical data (Cameron, 2019; Robbins et al., 2019). Our goal was to observe the differences between how faculty members and students viewed graphical data. We found that faculty and students differed in the ways and order in which they scanned graphs. For example, compared to students, faculty, who had higher graph literacy, had longer dwell times and more fixations on graphical features that are crucial to understanding, such as axes, labels, and legends. From these findings, we surmise that faculty spend more time than students engaging with these important features. This also led us to suspect that a lack of attention to key features contributes to the difficulties that faculty members report in students' attempts to describe graphical data (Cameron & Duffy, 2025). Unfortunately, our pilot study revealed that scan patterns were quite idiosyncratic across students and faculty, and it did not reveal conclusively the series of mental processes involved in graph reading; thus, we have turned to Decoding the Disciplines.

1.2 Decoding the Disciplines

An alternative approach to revealing the mental processes of disciplinary experts is Decoding the Disciplines (DtD), which can help students in their 'disciplinary thinking' by breaking academic tasks down into discrete steps (Middendorf & Shopkow, 2018; Pace, 2017)[1]. DtD was designed for and is typically used by experts in any field where specialized knowledge is developed over time.

In this study, we focused on Step Two in the DtD framework where interviewees break down their mental processes in a 'Decoding interview'. In a typical Decoding interview, the interviewers (who are typically instructors themselves) ask a faculty expert to explain how they approach a specific academic task, known as a 'bottleneck,' in a step-by-step manner. A bottleneck is a task that students struggle to complete, as evidenced by instructor feedback, yet is crucial to their success in the discipline. Previous work has established graph reading as a bottleneck across various academic disciplines (Cameron, 2019; Glazer, 2011).

In a series of three Decoding interviews investigating the mental moves that faculty members make while reading graphical data, we found that faculty members from three disparate disciplines reported utilizing a very similar series of steps (Cameron & Duffy, 2025, in this volume). Cameron and Duffy describe the steps faculty members take as they interpret graphs that their students have struggled with during assessment and class discussions. These faculty interviewees stressed the importance of orienting themselves to the graph by examining axes, considering the method by which data were collected, and only after they understood the context of the graph, did they focus on the trends in the data and determining whether there was statistical significance.

Given the differential responses of students and faculty in the pilot eye-movement study and the data obtained by conducting faculty Decoding interviews, we were interested in examining the underlying mental processes that students report using. To our knowledge, only three other studies have used Decoding interviews with students. The disciplinary tasks examined in these studies include examining how students write literature reviews in political science (Rouse et al., 2017), select credible sources (McBrady, 2022), and comprehend source code in the computer science discipline (Khomokhoana & Nel, 2020).

1.3 Students as Partners

In the pedagogical approach known as Students as Partners (SaP) within the scholarship of teaching and learning context, students and faculty work together to investigate ways to improve teaching and learning. Everyone involved is a stakeholder in the research. Partnership is a 'reciprocal process through which all participants have the opportunity to contribute equally, although not necessarily in the same ways, to curricular or pedagogical conceptualization, decision-making, implementation, investigation, or analysis' (Cook-Sather et al., 2014, pp. 6–7). In the current study, we have applied the collaborative nature of this approach to our methodology by conducting this work as a faculty-student team with mutual investment in the topic rather than the traditional approach of a faculty member who determines the focus of the research and supervises a student researcher/assistant. We believe that it is important to include students in research that is relevant to their own learning because they bring a valuable perspective that faculty, who are often relatively removed from the experience of being a novice in their discipline, may overlook (Pelnar et al., 2020; McBrady et al., 2021). Students involved in SaP collaborations might feel more comfortable sharing insights from their own experiences than they would in a more traditional faculty-student relationship in a research context. These collaborations can be highly successful given that student partners tend to be highly motivated when working with topics that affect them directly (Pelnar et al., 2020). Furthermore, the use of student interviewers when conducting interviews with student participants, as we have done in this study, is important in minimizing the risk of an unbalanced power dynamic between students and faculty that could impact the way students respond (Pelnar et al., 2020; Rouse et al., 2017).

1 For more information about Decoding the Disciplines, see http://decodingthedisciplines.org/

1.4 Objectives and Hypotheses

The goal of the current study was to explore a modification to the traditional approach of DtD with student partners interviewing non-expert graph readers. We expected to find that although students might experience the interview to be challenging, they would be able to describe their mental processes to the interviewers, allowing us to explore their range of mental moves. Given our previous findings (Cameron, 2019; Robbins et al., 2019), we did not expect to find consistent steps or strategies across student participants. Our goal was not to make generalizations about how all students read graphs, rather, we wanted to highlight the inconsistencies we suspected from students in comparison to the consistencies we found in faculty, which are described separately within this volume (Cameron & Duffy, 2025). Ultimately, we wanted to explore the possibility that the integration of two disparate approaches (DtD and SaP) would create a deeper insight into the teaching and learning of graphical literacy that would benefit students and educators alike.

2 Method

2.1 Participants

Eleven undergraduate students (two males) from a small Midwestern liberal arts college were interviewed for this study. All participants were compensated with their choice of either course credit or a 5 USD gift card. All participants were psychology majors, psychology minors, or enrolled in a psychology course. Two participants were seniors (fourth year), six were juniors (third year), and three were sophomores (second year).

2.2 Materials

The first three interviews were conducted in a laboratory setting, but given the COVID-19 pandemic, the remaining interviews were conducted via Google Meet. All interviews were audio-recorded and transcribed by the two student interviewers. These transcriptions are available on the Open Science Framework[2]. There were no systematic differences between in-person and virtual interviews in terms of length of interview, clarity, or amount of information provided.

2.3 Procedure

This study was approved by the Carthage College Institutional Review Board (IRB# 1145837). Semi-structured interviews were conducted by two student researchers (including the first author of this paper) in order to reduce power dynamics and maximize the likelihood that students would share their thoughts and challenges honestly. Both student researchers were juniors majoring in psychology. The student researchers had transcribed the faculty interviews (Cameron & Duffy, 2025) and discussed them in-depth with the faculty advisor (the second author), so they were familiar with the steps of DtD, particularly the Interview (Step Two). They also completed a pilot interview and received feedback from the faculty advisor.

Before the interviews began, all participants sketched a graph that they either generated from scratch or that they recalled. Those who were interviewed virtually either described their graphs for the interviewers to draw or held the graph up to the camera so that the interviewers could take a screenshot of the graph. All participants' graphs can be found on Open Science Framework[2]. We asked participants to provide their own graph because in our eye-tracking pilot study (Cameron, 2019; Robbins et al., 2019), the graphs presented to participants were created to mimic those found in an introductory psychology textbook. We found that some participants, including faculty, were unfamiliar with certain graph types and/or variables and as a result, became anxious or frustrated with the task. Thus, we reasoned that having generated their own graph, participants would be more comfortable and confident describing it and their mental processes. Also, because we were more interested in

2 To see interview transcripts and student graphs, please see https://osf.io/wmj25/?view_only=56a49e0eba9c4ba79dd749beaf98eadd

analyzing each participant's reported thought processes rather than their familiarity with graphs on psychological topics, we thought participants would be able to focus more on describing their thought processes if they were not distracted by topics of our choosing.

As is the practice in DtD, the interviews were semi-structured (Decoding the Disciplines, n. d.). The interviewers started by asking general questions to have participants describe as much of their mental processes as possible without directing the responses. Common questions that the interviewers asked included, 'When first presented with a graph, what is the first thing you do?' 'What do you look at next?' and 'What information are you hoping to get from that?' In many cases, the participants' descriptions did not address all the features within a graph (e. g., titles) or left out specific details. In these cases, interviewers followed up with specific questions about those features. The interviews ended once participants had explained their strategies as clearly and in as much detail as they could.

2.4 Data Analysis

The two students who conducted the interviews also transcribed them, and they and the faculty co-investigator ensured that the transcriptions were accurate. A set of codes were established based on the findings of the eye-tracking pilot study (Cameron, 2019; Robbins et al., 2019) and the faculty Decoding interviews (Cameron & Duffy, 2025). The codes included evidence of orientation to the graph, focus on trends or specific data points, use of title, and consistent strategy. See Table 1 for a description of the codes and examples of each. After coding each transcription, the student and faculty researchers agreed by consensus on each application.

Table 1: Codes Used for Data Analysis

Code	Description	Example
Evidence of orientation	Did participants indicate that they start by orienting themselves to the variables instead of trying to analyze the data immediately?	Yes: 'I start by looking at the y-axis so that I know what is being measured.' OR No: 'I start by looking at the direction that the data points are going in.'
Focus on trends or specific data points	Do participants indicate focusing on the overall trend in the graph rather than trying to analyze individual data points?	Yes: 'I look at the direction that the line is going and how much it increases.' OR No: 'I look at each point and see where it is on the y-axis.'
Use of title	Do participants utilize the title and for what purpose?	Yes: 'I look at the title first to get a sense of what the graph is about.' OR No: 'The title does not tell me anything that I cannot figure out on my own, so I do not really pay attention to it.'
Consistent strategy	Do the participants show evidence that they have a clear and consistent strategy?	Yes: 'Well whenever I look at a graph, I start by trying to figure out what the research question is.' OR No: 'I guess I start by looking at the title and then my eyes just move across the graph.'

Note. The examples listed are not actual quotes from participants, rather they are hypothetical quotes created by the researchers to demonstrate the themes we were looking for when coding.

3 Results

All participants completed the Decoding interviews with student interviewers, which ranged from five to 20 minutes in length and resulted in 136 minutes of audio recordings. As is sometimes observed in faculty Decoding interviews, some students had difficulty describing their mental processes. Many participants indicated that they had never before been asked to perform a metacognitive task such as describing their own mental processes in the context of graph reading. Moreover, there was much variability in the types, completeness, and complexity of graphs drawn by interviewees. Examples of such graphs include bell curves without axis labels, bar graphs displaying a frequency distribution of favorite colors, and a multivariate line graph with abstract labels. Some participants listed their series of steps with too little detail and/or with multiple steps combined, while others needed quite a bit of prodding. It was difficult for many participants to articulate their own mental processes while imagining reading a graph, and even with student/peer interviewers, many participants admitted to being nervous.

Six participants finished explaining their self-generated list of steps without mentioning features (e. g., titles and figure captions) that the researchers had previously identified as key features of a graph. When this happened, the interviewers waited until the participants indicated that they were done explaining their mental processes and then asked the participants about these features. Many participants indicated, once they had been reminded, that these features were important to their understanding of quantitative data. They would then indicate where they thought they would find that feature in the order of steps they had identified. Table 2 highlights the variability in the number and order of steps that each participant reported using while reading graphical data. For comparison, we included the steps reported by faculty in the last row (Cameron & Duffy, 2025). It is important to note that Cameron and Duffy found consistency in the steps and order reported by three faculty members. The same was not true for students, who differed greatly in their reported processes. Furthermore, none of the students reported a series of steps that matched those of the faculty.

Despite the difficulties that some students had when trying to articulate their mental processes, sometimes a student's vagueness revealed as much as another's detailed account. For example, when asked why they start by examining the 'data display,' P4 stated,

> I think it's just the outcome of why I'm looking at this graph. I think I'm just trying to understand- I'm trying to understand it better, so I'm not looking at it with no clue. I'm just trying to look at it so then I know what I'm looking at.

Such vagueness and circularity indicate difficulty both in talking about graphical data and in breaking down their own mental processes. The students struggled metacognitively to understand how they approach data as they realized it is not as self-evident as they may have previously believed.

Table 2: Participants' Self-Reported Order of Steps During Graph Reading

Participant (class/major)	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1 (senior/ psychology & neuroscience)	Figure caption	x-axis label	Visual data	y-axis label	y-axis scale	Other features	Title
2 (senior/ psychology & neuroscience)	Title	Axes labels	Visual data	Axes scales			
3 (junior/ psychology)	Figure caption	y-axis	x-axis label	x-axis scale	Visual data		
4 (junior/ psychology & neuroscience)	Visual data	x-axis label	y-axis label	Title	Axes scales		
5 (junior/ psychology)	Axes	Individual data points	Trends	Figure caption	Back to visual data		
6 (sophomore/ psychology)	Visual data	Axes	Legends	Outliers	Other relationships	Title	Figure captions

(Continuing table 2)

Participant (class/major)	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
7 (junior/ psychology)	Background info	y axis label	y axis scale	x-axis label	x-axis scale	Conditions of indepen-dent vari-ables	Figure caption
8 (sophomore/ psychology & environmental science)	Title	x-axis	Clusters; visual data	y-axis label	Visual data	Statistics	
9 (sophomore/ English)	Title	Variables	Background information	Figure caption	Visual data		
10 (junior/ psychology & sociology)	Data starting point	Title	Axes labels	Trends	Figure caption		
11 (junior/ criminal justice)	Title	Figure caption	Visual data	Variables	Outliers		
Faculty example (Cameron, 2024)	Y-axis	X-axis	Visual data	Title	Figure caption	Statistics	

Note. We have included class standing and major for each participant, but our sample size is not large enough to draw any conclusions about how these factors may have affected each participant's reported graph-reading process.

3.1 Variability in Graph-Reading Steps

While there was plenty of variability in the students' ability to break down their mental processes, the Decoding interviews were largely successful in that they provided insight as to how students attempt to read graphical data. The number of steps participants identified in interpreting graphical data ranged between four and seven, with an average of five steps (see Table 2 for the list of these steps). Some students, such as P7, described their graph-reading process in great detail. For example, they specified that looking at the x-axis label, y-axis label, x-axis scale, and y-axis scale are their own discrete steps in their mental process. This was rather uncommon, as most participants tended to speak about the labels and scales as a single or two steps as opposed to four. On the contrary, P2 listed only four steps in their graph-reading process. They grouped looking at the axes labels as one step and the axes scales as another, purportedly looking only at those, the title, and the data trends.

3.2 Consistent Strategy Among Students

Although participants did identify a list of steps that they use, only five of the participants interviewed appeared to have a consistent strategy for reading graphical data. The interviewers inferred a participant's consistency through clearly articulated descriptions of steps and the use of words such as 'always' that indicate regularity. These participants could seamlessly describe their mental steps to the interviewers as well as explain why they did each step. P7 explained, 'I think as far as steps, I keep the same steps for the most part.' Likewise, P8 very confidently described their strategy indicating that,

> I would always start by looking at the x-axis, like what A1 and A2 are because then I know if I'm looking at like time points or if I'm like, looking at heights or any kind of variable. I always look at that first to see what I'm measuring of the other variable across. And then I look at each individual line that's on the graph to see what that variable is.

In contrast, the remaining six participants did not seem to have a consistent set of steps or strategies for reading graphical data. Several of the participants came to realize that they had not previously thought of graph reading as a process. They described looking at surface-level elements (i. e., titles and overall trends), but could not describe how they gather information that is not self-evident. These participants did not know how to go beneath the surface of a visual display to truly understand the meaning of the data. P6 became slightly frustrated when they were prompted to break down their mental processes and struggled to do so. They stressed,

> Because I don't know if I have a specific order. I think, most of the times, I start by looking at the graph and trying to see if there's a relation and then I'm like, "Oh well I need more information," so then I look around- look around the graph and it's kind of just where my eyes go.

P4 was also unable to clearly describe their thought process. During the interview, they became overwhelmed and started to contradict themself, stating,

> Normally, when I look at a graph- there's a lot of information in front me, so I kind of- I don't know where to look so I first look at the figures, like if there are lines, there's little graphs or something like that. After that, I start analyzing it, or the information that I know about the graph. I look at the x-axis, the y-axis to see what information there is there and what it's trying to say. I try not to look at the title because I feel like it can sometimes be a little bit misleading or it doesn't tell you what I want to know- it does tell me like, what it's about, but it doesn't tell me like the information. After that, I just start looking at the information one-by-one.

3.3 Other Reported Mental Processes

Several other aspects of students' approaches became apparent in the Decoding interviews. Seven of the participants indicated orienting themselves to the graph before analyzing the data (see Table 2). They described doing so by looking at elements like the variables, title, and figure captions before looking at the visual display of the data. P2 explained that this makes interpreting the graph much easier because the title and axis labels assist in 'understanding what [the researchers are] looking for in their data.' The remaining four participants indicated that they prioritize looking at the relationships between the variables. For this reason, they examine the visual display of data before trying to figure out what the variables represent.

Another difference among participants' mental strategies was whether they focused on the overall trends in the data or on specific data points. The majority (nine) of participants indicated that they do not focus on individual data points. When examining the visual data contained within a graph, they try to understand the main trend and disregard individual data points unless the graph contains outliers. The remaining two participants indicated that they like to examine each individual data point before drawing conclusions about the trend.

In terms of graph titles, nearly half (five) of participants considered them to be important, citing them as the first or second feature that they view. P2 stressed the importance of looking at the title during their graph-reading process. They exclaimed, 'Obviously, I read the title!' when asked what their first step is. Two other participants indicated that the title was important to their graph-reading process but explained that they looked at it last. P1 explained, 'I probably look at the title last. I try to examine what's going on first and make my own conclusions.' In their graph-reading process, reading the title last helped them verify their conclusions about the graph. Conversely, three participants indicated that they do not look at titles at all considering that many graphs do not contain titles, and in their perspective, titles are often self-evident

3.4 Additional Insights

One important insight is that many participants highlighted that they often do not view graph reading as a procedure with distinct steps. One participant (identified as P2) described graph reading as something that people 'just do it. Like you don't actually think about it.' This suggests that such students view graph reading as self-evident. They take in obvious features within the visual display but do not delve into the meaning and significance of the data that the graph is conveying.

4 Discussion

The aim of the current study was to explore the use of Decoding interviews with non-expert interviewees as well as student interviewers. We believe there is much to gain from these two methodologies and hope to see their use expand in novel ways, just as we have done in this study. Ultimately, we hope to give students and faculty alike more insight into the graph-reading processes and the ways that these could be more effectively taught and learned.

Overall, the application of Decoding interviews by student partners with non-experts was successful as we were able to complete all 11 interviews and gain insight into students' unique processes, knowledge, and challenges in graph reading. While the level of metacognition required during Decoding interviews was difficult for our participants, a majority of them were able to convey their thought processes to interviewers with the help of prompting questions. Students provided less information about their mental processes than faculty as evidenced by the fact that the student interviews lasted a maximum of 20 minutes, whereas faculty interviews lasted approximately an hour (Cameron & Duffy, 2025). We do not think this reflects negatively on the approach, but rather, that students simply have less to say about their graph-reading processes.

While students have been interviewed using the 'think-aloud' procedure in the past (e. g., Trickett & Trafton, 2007), the use of Decoding interviews with students is a unique approach and, to our knowledge, has been applied in only three studies (Khomokhoana & Nel, 2020; McBrady, 2022; Rouse et al., 2017). Whereas the 'think-aloud' procedure involves participants guiding the interviewer through the logic of their explicit responses as they complete a task, Decoding interviews ask students to introspect and make explicit their implicit mental processes. During Decoding interviews, students in the current study were able to articulate a series of steps in their graph reading, and there was a great deal of variability in the steps reported. We found that many students did not report a consistent strategy in their reading of graphical data. Many revealed that they had not previously conceived of graph reading as a task requiring a set of discrete steps. The findings of this study contrast with those of a study of faculty, who appear to use and can describe a consistent set of mental processes in graph reading (Cameron & Duffy, 2025). These faculty also recognized the importance of delving into the significance of the data beyond that which is self-evident.

In Decoding interviews, faculty members stressed the importance of two steps: (1) Orienting oneself to the graph, and (2) Focusing on trends rather than individual data points (Cameron & Duffy, 2025). They also cited, anecdotally, that these two steps were often missed by many of their students, in accord with Zucker et al (Zucker et al., 2015). Likewise, in a systematic analysis of student responses to an assignment that involved reading a graph and providing a description of it, some of the most common mistakes that students made revolved around orientation to the graph (Bousson, 2024). This included issues of omitting relevant variables, introducing unrelated variables, and misrepresenting variables. Interestingly, we found that most students in the current study (seven) described orienting themselves to the graph and nine out of eleven indicated that they do not focus on individual data points. This is encouraging, but begs the question: Why did faculty highlight these issues? With respect to orienting to the graph, one possibility is that while students recognize that they need to do so for themselves, they are less likely to orient their audience when communicating about graphical data, the situation on which the faculty may have been reflecting. Explicitly orienting the audience to a graph may be a step that requires more direct instruction, especially when we also consider the increased amount of time that faculty spent looking at orienting features (i. e., axes, labels, and legends) in the pilot study (Cameron, 2019; Robbins et al., 2019). With respect to both orienting to the graph and not focusing on individual data points, it is also possible that there is a sampling bias and that these 11 students (the majority of whom were juniors and seniors) had already developed these skills. Thus, the faculty may have been reflecting on the performance of less advanced students. Future research could focus on the development of these skills over the undergraduate years.

Our merging of Decoding and SaP approaches created a unique opportunity for both students and instructors to learn about the graph-reading process (McBrady et al., 2021). Both the student interviewers and some of the interviewees expressed that the Decoding interviews helped them begin to reflect on their own mental processes more clearly and led them to consider adopting a more strategic approach to graph reading. We agree with Glazer (2011) that explicit instruction on graph reading, and perhaps on the importance of describing graphs to an audience, is warranted. Interestingly, two psychology undergraduate students in the current study indicated that they would benefit from, or already had benefited from, being taught how to read a graph more explicitly and in a step-by-step manner. Additionally, after reading the transcripts of the Decoding interviews and discussing them with the student interviewers, faculty involved in this project gained crucial insight into the perspectives of students. For example, student partners were able shed light on the important role of motivation when it comes to students taking the needed time to fully understand a graph. As student partners pointed out, a lack of understanding may sometimes reflect a lack of motivation. Graph reading develops incrementally and cannot be assumed to be a competency acquired in secondary education (Borner et al., 2019).

We also would like to emphasize the importance of SaP work as it is rewarding for all involved (Pelnar et al., 2020). Students are given the chance to engage in work that is directly related to their own learning and acknowledge that they are contributing a valuable perspective to the research. Students involved learn about their own understanding as well as how to improve their skills and knowledge, while the faculty involved have the opportunity to learn about the efficacy of different teaching approaches. Moreover, faculty can gain insight into the student perspective, which typically, they are far removed from themselves after achieving 'expertise' in the field. Both authors of this paper benefitted from this collaboration in that they developed greater insight into how they interpret (first author) and teach (second author) quantitative data.

4.1 Limitations

Conducting Decoding interviews presents some challenges. Some people may be less willing to explore and describe their mental processes than others. Indeed, faculty interviews lasted much longer than those with students. That is not to say that the difficulty in Decoding interviews is unique to students, as faculty sometimes also struggle and 'get stuck' (D. Pace, personal communication, November 2, 2020). During some of the interviews, the interviewers struggled to maintain a conversation with the participants. These participants made it clear that graph reading was not something that they consciously thought about and being asked to do so was a difficult task. Some participants either struggled to understand the questions that were being asked of them or could not articulate their thoughts clearly.

Although the sample size in this study (n = 11) may appear to be small and to limit our ability to generalize, it is consistent with other DtD studies, in which the goal of the study is to investigate individual mental processes in depth. In fact, our sample size is in line with the other studies of this type (e. g., McBrady, 2022; Rouse et al., 2017). Notwithstanding this limitation, our data do indicate variability in graph-reading skill, with some but not all students identifying clear and consistent steps. This supports our contention that further explicit instruction would be valuable, at least for psychology undergraduate students.

4.2 Future Directions

Given the trends in previous literature surrounding DtD and SaP work, further research using these two approaches is likely to be fruitful. Thus far, they appear to yield promising utility and valuable insight. However, research into merging these approaches remains limited. Future work expanding the use of DtD and SaP, either alone or in tandem, will further our understanding of learning and collaboration in educational settings and beyond.

In this and another study (Cameron & Duffy, 2025), we have completed Steps One and Two of DtD. First, graph reading has been identified as a 'bottleneck' in student learning (Cameron, 2019; Glazer, 2011; Pace, 2017). Second, we have identified the steps that faculty experts (Cameron & Duffy, 2025) and students (the current study) utilize. Here we have provided evidence of a lack of consistent strategy among students. As noted previously, many students do not perceive graph reading as a stepwise task. The findings of this study could be leveraged to help students recognize the important function that these metacognitive steps serve. In Step Three of Decoding, instructors model a skill for their students and in Step Four, students practice this task. That work is currently underway in our lab and classroom. Our current efforts are directed at identifying teaching methodologies that can most effectively help students overcome the bottleneck of graph reading. This requires balancing time spent on course content and developing skills.

In the future, we hope that more instructors might consider decoding their own mental processes, particularly in graph reading, and use it to inform their modeling of this crucial skill. While it will initially take some time for the educator to model a task and have students practice completing it, this will save time in the future as students will overcome the bottleneck and be able to complete the task more quickly and effortlessly in future lessons and courses. Future research should also investigate whether some methods of modeling are more effective than others.

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Applying *Decoding* Methodology to Psychological Statistics and Other Applications

Lisa Jo Elliott, Joan Middendorf

Abstract

This article summarizes a recent study of *Decoding the Disciplines* applied to psychological statistics and explores the methodology behind the scenes that facilitated the project. The first part of the paper will summarize the study. The second part will highlight aspects of the *Decoding* methodology that enhanced the research project, a non-interview form of *Decoding* and the advantage of cross-disciplinary collaboration. The third part of the paper points to other applications of the methodology and discusses numerous ways instructors have used *Decoding* methodology and theory in their SoTL (Scholarship of Teaching and Learning).

Keywords Decoding the Disciplines; analogy; pedagogy; methodology; bottlenecks; SoTL; teaching methods

Anwendung der Decoding-Methode auf Statistik in der Psychologie und weitere Kontexte

Zusammenfassung

Dieser Artikel fasst eine Studie über die Adressierung von Lernhürden von Studierenden in einem Statistikkurs im Kontext von Psychologie zusammen und stellt vor, wie Decoding the Disciplines als Konzept eingesetzt wurde, um den Kurs zu verbessern. Im ersten Teil des Artikels wird die Studie zusammengefasst. Im zweiten Teil werden Aspekte der Dekodierungsmethodik genauer beschrieben, die zur Reflexion der Lernhürden beigetragen haben, konkret die Nutzung von Analogien in einem interdisziplinären Kontext. Der dritte Teil des Artikels weist auf weitere Anwendungen der Methodik hin, indem er Möglichkeiten beschreibt, wie die Decoding-Methodik und -Theorie in verschiedenen Stadien des Konzepts eingesetzt wurden.

Schlüsselwörter Decoding the Disciplines; Analogien; Methodik; Lernhürden; SoTL; Lehrmethoden

1 Introduction

Instructors who use *Decoding the Disciplines* report anecdotally that it improves student learning, but few published studies have shown quantitative evidence that learning improves with *Decoding*. For readers who are unfamiliar with *Decoding*, an in-depth description of the methodology can be found in Middendorf and Shopkow (2018), Miller-Young and Boman (2017), and Pace (2017). Three studies (Pinnow, 2016; Lee-Post, 2019; Elliott & Middendorf, 2024) demonstrate a statistically significant difference in student learning when the *Decoding the Disciplines* method is used to develop course materials. Specifically, Pinnow (2016) taught an introduction to psychology class and used *Decoding* to create new curriculum addressing the cognitive bottleneck-"applying the scientific method." She tested three subtasks within this bottleneck and found that the *Decoding* curriculum increased student learning significantly. As Pinnow (2016) suggested, student understanding of the scientific method in psychology determined mastery of an understanding of psychology as a science.

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Lee-Post (2019) taught a business operations analytics course and used Decoding to address one cognitive and one affective bottleneck. The cognitive bottleneck-"building models" and the affective bottleneck-"low self-efficacy in numeracy," as well as the pre-conception that the course is demanding, were addressed across two semesters: summer and fall. Lee-Post found that students in either of the Decoding classes had significantly higher test scores than students who were in the regular classes. And as Lee-Post (2019) noted, self-efficacy and a course's challenging reputation can be detrimental to student learning when left unaddressed.

In Elliott and Middendorf (2024), Elliott taught an introduction to psychological statistics course and used Decoding to address five cognitive bottlenecks and student attitudes (including affective bottlenecks) towards the course[1]. The bottlenecks were addressed in the first four weeks of class with Decoding lessons. Previously, the instructor had taught four weeks of introductory definitions and beginning research. Because the authors will describe aspects of the methodology that guided the psychological statistics study, an example of one of the lessons, variability, will be outlined here. However, readers are encouraged to consult the original published article.

To show how Decoding the Disciplines functions at every step of a bottleneck lesson, Figure 1 delineates in brief the steps of the variability bottleneck lesson. Following Figure 1, we describe how the methodology applies to the variability lesson. Following that is a transcription of the authors' conversation to illustrate the depth of work and the cross-disciplinary collaboration necessary for the analogy approach to creating a Decoding lesson.

1 The initial draft of this paper was originally presented at the first *Decoding the Disciplines* conference in Aachen, Germany in November 2023 (Elliott & Middendorf, 2023).

1. Bottleneck: Difficulty visualizing variability patterns in the data.
2. Decode: Visualize the distance between the numbers in the data sets to reveal the pattern within and across the groups.
3. Model: Like the combination of notes and spaces in music, both the distance between the numbers and the regularity. Is it a steady beat like a marching drum or is it improvisational like jazz? OR like viewing the patterns on dice or dominoes at a glance, without counting by ones.
4. Practice: Students make a "human graph" by standing close together or far apart to emphasize the spacing in between a given set of numbers (Wentworth, n. d.).
5. Motivate: To avoid math phobia and to address a feeling of competency with numbers, use numbers less than 100 in the first weeks. Practice together in class.
6. Assess: Pre- and post-test with multiple choice questions on variability. Muddiest point CAT (Angelo & Cross, 2012).
7. Share: Presenting this paper at Aachen *Decoding* Conference (Elliott & Middendorf, 2023).

Figure 1: An Overview of the Variability Bottleneck Lesson

To create this lesson, the authors followed these explicit steps which are slightly different from other versions of *Decoding. Decoding* required new thinking at each of the steps to develop this lesson, which we are explaining in detail.

Step 1 – Determining the bottleneck. A bottleneck lesson starts at a place in the course where the instructor notices that students repeatedly struggle to understand something; in this example, the concept of variability. For this bottleneck, students struggle to recognize the patterns in the data that indicate significance. Subitizing is a sub-bottleneck of variability; by focusing on the problematic sub-bottleneck, that is, breaking the problem into its parts, learning can be better scaffolded, and students can take on more difficult tasks (Middendorf & Shopkow, 2018).

***Step 2 – Decoding the mental move*.** The instructor as specialist quickly visualizes the spaces between the numbers in the data sets, examining the distance and regularity within and between the numbers that determine variability. The specialist can visualize the spaces between the numbers without counting or measuring them to tell if the spacing is far apart/not far apart and regular/or irregular. Once the spacing is determined, the next 4 steps of *Decoding the Disciplines* use pedagogical theory to suggest instructional strategies.

Step 3 – Modeling. The instructor presents an analogy for the mental move, placing it in a familiar context so that the pattern of significance would be evident to students through the relational structure.

Step 4 – Student practice. Both in-class and out-of-class practice exercises allow students to try out the mental move, not just passively watch the instructor perform it.

***Step 5 – Motivate*.** Students often need help to persist in trying a new mental move. Building new neural connections is difficult, possibly even painful work, and takes repeated practice built into the course structure to solidify them. The motivation step encourages instructors to check for any spots in the course that are notably difficult or that students especially resist-and make a plan to get through these most difficult of difficulties.

In this course there were affective bottlenecks of self-efficacy and math anxiety. For the first part of the course, the restructured lesson plans aimed to avoid math anxiety. Thus, all numeric examples involved numbers less than 100. For self-efficacy, students practice problem-solving exercises in teams with their whole selves and interact with classmates, such as the human graph, whereby people stand along a number line to represent a numeric answer or their attitude toward a controversial idea (Wentworth, n. d.). The social engagement allows students to try out new concepts before working on individual homework, thus building confidence in use of statistical concepts.

Lee-Post (2019) noted that in a key business course, students struggled with both cognitive bottlenecks and affective bottlenecks. For the cognitive bottlenecks, students struggled with quantitative modeling. For the affective bottlenecks, students believed that the course was demanding and not relevant and argued that these should be addressed simultaneously. The authors of the current study took a different approach to a similar affective bottleneck.

Middendorf & Shopkow (2018) argue in *Overcoming Bottlenecks* Chapter 5 that even with strong modeling and practice of the cognitive bottlenecks, if student learning difficulties persist, affective obstacles, also known as emotional bottlenecks, may be prohibiting students from resolving the cognitive bottlenecks. With a focus on the Motivation Step, the instructor can assess key motivational factors. Are disciplinary procedures or worldviews impeding the learning? These types of challenges, which can be assessed, appear in the pre-existing narratives students bring to the course. The instructor is then in a better position to address student resistance by, for example, explaining the reasons for certain disciplinary procedures to students (such as daily homework or following the desired routine for problem-solving). If the results of the assessment reveal the worldview as the source of resistance, the instructor may need to begin by addressing student prior self-beliefs, such as "I'm not good at math" or "this class is too hard for me." If not addressed, affective/emotional bottlenecks can continue to interfere with learning.

Step 6 – Assessment. Student competence was measured on the bottleneck of variability through open ended qualitative questions and multiple-choice quantitative questions.

Step 7 – Sharing. *Decoding the Disciplines* eases entry into scholarship of teaching and learning (SoTL) (Middendorf & Pace, 2008). During the session in which this paper was originally presented, conference participants were invited to discuss *Decoding* studies in their fields, which resulted in a wide-ranging discussion. Even novice instructors can build and assess a 7-step bottleneck lesson, or even for simplicity's sake choose to use just one or two steps of the model as the basis for a study.

The methodology used to create the variability bottleneck was similarly followed for the other four bottlenecks in the study (probability, central limit theorem, independent/dependent variables, and degrees of freedom) and these bottleneck lessons are available from the authors on request.

2 Advantages of the Methodology for Students

Qualitative data from student responses (Elliott & Middendorf, 2024) suggested that the *Decoding* lessons helped alleviate anxiety towards the course material. The results described a decrease in students' anxiety, and increase in confidence in their own competency, and a more favorable perception of the course. One student wrote:

> "Making mistakes is a part of learning, so it is okay to make them. However, you must learn from them. Redoing assignments allows you to have more practice and learn from the mistake you made…. Finally, the other main thing you do is understand the conceptual parts of the analyses. Understanding the conceptual parts of the analyses will make them much easier to understand and complete…"

Another student had a similar response:

> "… I am sure everyone has heard that 'statistics is so hard,' I would know because I used to say that despite not having any knowledge of the concepts of stats… Don't allow the stigma around stats being so difficult influence you from succeeding in this course."

The *Decoding the Disciplines* method resulted in lessons that significantly improved student learning on the five core concepts. Informal feedback suggested that students felt the course was more enjoyable and that they felt confident in their ability to perform statistical analyses.

3 Advantages of the Methodology for Instructors

As the *Decoding* lessons took place in the first few weeks of the course, the instructor assumed that these concepts would have to be retaught as the individual statistical tests were taught. This was how the course progressed in the past; students would forget what they learned in the first four weeks and how that applied when they actually did the analyses. The instructor observed that this was no longer the case. Students had retained what variability meant so when the discussions of the different types of measures of variability ensued (e. g., standard deviation, standard error, mean square error, etc.) students understood the concept in general and focused on how variability was calculated in a specific type of statistical analysis. This saved the instructor time and additional teaching effort. This was a novel and unexpected by-product.

4 Comments on the Decoding Methodology

Besides highlighting the use of all seven steps of the methodology, the authors believe two aspects of their collaboration also merit reflection because they are key to the success of the methodology: The non-interview, analogy-trading approach to *Decoding* the mental move; and the value of cross-disciplinary teamwork.

4.1 The Non-interview Analogies Methodology for Uncovering Mental Moves

The authors used a non-interview form of *Decoding* for this project, which is explained in detail.

In *Decoding* interviews, the interviewer probes the specialist, again and again, to get the specialist to further analyze their implicit critical thinking into its parts. But there are other forms of *Decoding* that can achieve the same results. Step 2 *Decoding* involves unpacking someone's implicit mental processes, where the specialist can do a lot of things fast and in large chunks (Chi et al., 2014), yet it is not readily available to the specialist to examine what is going on in their own mind. Analogies can shine a light on a specialist's critical reasoning because analogies can offer clues to understanding hidden mental models (Elliott & Foltz, 2005). Analogies are also effective in communicating difficult concepts. For example, medical professionals concerned that patients do not understand probability enough to make an educated decision about treatment options have turned to analogies (among other non-numeric explanations) to communicate the probability of different health outcomes to their patients (Galesic & Garcia-Retamero, 2010).

For this project, the authors traded analogies to uncover the mental move. Not being a STEM scientist herself, and without a co-interviewer from within the discipline, Middendorf was not confident that a *Decoding* interview would make the mental moves clear. Also, she finds the trading analogies approach more enjoyable, stress-free, and effective at uncovering the mental move.

To start, Elliott explained the mental move to Middendorf the best she could and, to check Middendorf's understanding, Middendorf offered her an analogy for it. Is it like this? Whatever analogy popped into her mind. With the variability bottleneck, Elliott had started from an example about a tomato gardening experiment that featured two treatments, one with fertilizer and one without, looking for variability in the data results. To create the analogy, Middendorf took what she perceived as the mental move, removing it from one context and placing it in a different context. Below is the transcript of one of our discussions when trading analogies for the variability lesson described in the study above.

Middendorf: Can the two treatments be like comparing a holiday meal to a regular meal?

Elliott: No, it isn't like that. I don't know how you show the effect size for a holiday meal versus a regular meal. It's more like black boxes between the numbers in the data. If the numbers were (5, 10, 15, 20, 25) compared to another data set where the results were (3, 10, 11, 20, 24), the specialist visualizes the black box patterns (the spaces) in between the numbers.

Middendorf: It's like black boxes?

Elliott: Maybe that's not clear enough for you. It's like matching lids on Tupperware where it'll just snap together. When you look at those spaces between the numbers, you need the right fit.

Middendorf: It's like matching the lids for Tupperware to the containers? Hmm.

Elliott: It must be exact, and it'll just snap together. When you look at those spaces between the numbers, you need the right fit.

Middendorf: I'm looking for the right lid to Tupperware between the numbers?

Elliott: Maybe it's more like reading musical notation. Someone who can read the musical notes on a page and hear the music can hear the difference between quarter notes and 16th notes and know that the spaces between the notes mean something, that was like the spacing between the numbers for (5, 10, 15, 20, 25) which is 5-5-5-5--very regular, same amount of spacing, while the spacing in between the other seven numbers (3, 10, 11, 20, 24) are 7-1-9-4 is jumping all over, then you could see wow, there's a significant difference between these two data sets.

Middendorf: Is it like seeing the patterns on dominoes or dice, where we don't count by ones to see what number we have, but group numbers and see the pattern all at once?

Elliott: That works, because humans can only subitize 3–5 items at most, so they group numbers into clusters and then combine them for a total.

Middendorf has learned to place the mental move in a different context, even if the new context is far from the mark as a starting point. Very often, when suggesting an analogy, the receiver of the analogy will automatically either critique the analogy, or offer another analogy in reply, and that refines her idea of the mental moves. It's like a game of "Hot and Cold" with the analogy getting closer to the mental move and the specialist being the one who has a sense of when the analogy is getting warmer. Both Middendorf and Elliott enjoyed the experience, and it further uncovered the mental move.

- In addition to analogies, other forms of non-interview *Decoding* (Middendorf & Shopkow, 2018) include the following:
- Bottleneck writing tour: a reflective writing process with rounds of reiterative writing about the bottleneck and the mental move (Lahm, 2016).
- Concept or mind mapping or flow charting: drawing the steps or parts of mental move.
- Three-dimensional modeling: Using simple materials such as playdough, Legos, or sticks and grass from the garden to build a physical model of the mental move.
- Rubric building: Starting from a list of frequent mistakes students make and creating a corresponding list of the opposite of each mistake-a list of what the specialist does to avoid each mistake (Shopkow, 2017).

All the alternative *Decoding* methods involve conversation with an interlocutor, preferably one from a different discipline.

4.2 The Importance of Cross Disciplinary Dialogue

Some educational leaders encourage instructional support to come from specialists in the same field, such as a psychology specialist to support a psychology researcher or instructor. Decoding encourages the opposite, because an expert from the same field may find it difficult to notice leaps a specialist makes in their reasoning that may leave learners behind. Cross-disciplinary dialogue is powerful. Varpio and MacLeod (2020) note that when scholars from different traditions work together, each has a unique perspective on the world, and they each must "articulate their reasoning, theories, and values" (p. 687). The different traditions of working together combine the strengths of each field. Sometimes the more dissimilar the foundations are from each other, the better the end product that will emerge. This cross-disciplinary dynamic was at work in this project.

With *Decoding the Disciplines*, there is typically at least one person from inside the discipline, the specialist whose bottleneck and tacit critical thinking will be *decoded*, and at least one person from outside the discipline. The outside-the-discipline interlocutor's strength lies in not knowing, with continued probing, and not faking understanding that they do understand when they do not. This person (no matter what discipline they are from) trusts the *Decoding* process, and continues to uncover assumptions, until no assumption remains unturned.

As Varpio and MacLeod (2020) note, that intersection of the minds can be threatening but powerful. One person must be comfortable not knowing; while the other must be confident knowing yet not being able to describe what is going on in their mind until the mental move has been re-amateurized by unpacking their expertise so it may be scaffolded for the students. The process rewires the instructor's or specialist's brain to see disciplinary concepts from the learners' viewpoint and value that viewpoint. *Decoding the Disciplines* method takes cooperation and trust.

When the collaboration is going well, the work may be difficult but not overly taxing; more like two mules harnessed together pulling a load downhill, not uphill; a shared partnership with no one person carrying more of the effort. We came out of the project with each of us feeling like the other author had made most of the effort.

Social norms such as gender perceptions and disciplinary norms can interfere. Both parties must understand that parsing assumptions can be somewhat uncomfortable or frustrating but leads to a better understanding. Patience and openness to new ideas from outside of one's discipline are key.

Applying the *Decoding* theory and methodology enabled the authors to identify difficult bottlenecks in learning psychological statistics, to uncover the "secret knowledge" of the statistics specialist by communicating through analogies, and to open up the insider knowledge for learners by taking advantage of the outside author's non-disciplinary viewpoint to re-amateurize the difficulties and question unopened assumptions about the critical reasoning to get through them. Through collaborating on this study, the instructor has improved the learning on the key bottlenecks in psychological statistics and learned to teach from a theory, one that allows her to confidently notice where the students are struggling, to frequently assess the stuck places, and to scaffold the mental moves with the pedagogical tools of analogies, practice, and motivational considerations. Thus, *Decoding* can guide her teaching in the future. Other instructors and SoTL researchers can use the *Decoding* methodology to enhance their work.

5 Other Applications of *Decoding* Methodology

The final step of the *Decoding* model, Step 7 Sharing, is the SoTL step. It encourages analysis and reflection of what one has learned from applying *Decoding* to one's teaching or research and includes going public with the results. The psychological statistics study exemplified a *Decoding* study that utilized all the steps of *Decoding the Disciplines*. Sometimes instructors or SoTL researchers choose to focus a *Decoding* study on one step only. A small representation of the discussion of these kinds of studies organized by the *Decoding* methodology, are listed below.

Step 1 Bottlenecks. McMillen and Magner (2023) studied pre-service elementary teachers who recognized their own bottlenecks in mathematical teaching and understanding.

Step 2 Decoding. Lindstrom et al. (2023) explained the *Disrupting the Disciplines* interview as an approach to reveal how disciplines may be upholding colonialism, racism, and assimilation of diverse identities.

Step 3 Modeling. In a tech-heavy course, Lee and Kramer (2023) modeled examples from outside of the technology to explain a piece of code to students.

Step 4 Practice. Mondelli (2023) combined *Decoding the Disciplines* with game design to ensure the practice efforts of a game were aimed specifically at the mental moves.

Step 5 Motivation. To lessen resistance and shift to a student-centered classroom, Wegner (2023) applied the students-as-partners approach through student-led *Decoding* interviews. In contrast, Nel (2023) showed the results of exploring emotional/affective bottlenecks using Social Dream-Drawing Techniques.

Step 6 Assessment. Darcy (2025) translated *Decoding* interviews into a checklist for interpreting biology graphs that, when surveyed, 79 % of beginning students in a large biology class found useful.

While elements of the *Decoding the Disciplines* model in the examples above with Steps 1–6 are valuable for SoTL and teaching, some researchers took a different approach, extending *Decoding* theory through complementary theories. For example, Yeo and Stalheim (2023) combined *Decoding* and hermeneutics to make the familiar strange in teacher education. Taczak et al. (2023) compared transfer and *Decoding the Disciplines* frameworks to promote lifelong learning. Brase et al. (2023) connected *Wissenschaftsdidaktik* (i. e., the scientific teaching methods) with research and teaching in the disciplines.

Some of the researchers explored further development of *Decoding the Disciplines* in new contexts, such as in teacher education (D'Sena, 2023; Beam et al., 2023), educational development (Riegler, 2023), and for new methods in Collaborative *Decoding* (Barnat & Foltz, 2023). These are just a few examples of the ways that by going public with findings, Step 7 of *Decoding* encourages analysis and inquiry in SoTL.

In summary, *Decoding* provides a methodology for instructors to teach based on theory that has demonstrated an improvement in student learning and gives an accessible entry point to SoTL by providing a theoretical framework. The psychological statistics study described in the article was an example that the authors used to explain their experiences with the *Decoding* methodology, in particular the use of analogies to uncover tacit mental moves in a beginning psychological statistics course and the usefulness of outsider-insider positionality in exploring disciplinary understanding.

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Disciplinary Dream-Drawings

An Innovative Methodology to Uncover Students' Emotional Bottlenecks

Liezel Nel

Abstract

Emotional bottlenecks significantly impede learning but are often overlooked in higher education. This paper explores the use of the Disciplinary Dream-Drawings (DDD) methodology, an adaptation of Mersky's Social Dream-Drawing, within the Decoding the Disciplines framework to uncover these hidden emotional challenges among first-year Computer Science students. Through a pilot study at a South African university, students created dream drawings and narratives reflecting their academic experiences. Analysis of the visual and narrative data revealed eleven primary emotional bottlenecks, including family and financial pressures, self-imposed expectations, feelings of inferiority, and stress related to coding activities. The findings highlight the complex interplay between personal and academic spheres and underscore the need for educators to address emotional barriers proactively. The paper discusses the potential pedagogical implications of implementing the DDD methodology and offers reflections on its execution, emphasizing how it can be utilised by educators to better support their students' emotional and academic development.

Keywords: Emotional Bottlenecks; Disciplinary Dream-Drawings; Social Dream-Drawing; Computer Science Education; Decoding the Disciplines

Traum-Skizzen aus der Disziplin

Ein innovativer Ansatz zur Identifikation emotionaler Lernhürden bei Studierenden

Zusammenfassung

Emotionale Hürden behindern das Lernen erheblich, werden jedoch in der Hochschulbildung oft übersehen. Dieser Artikel untersucht die Anwendung der Methodik „Disciplinary Dream-Drawings" (DDD), eine Anpassung von Merskys „Social Dream-Drawing", im Rahmen des „Decoding the Disciplines"-Ansatzes, um verborgene emotionale Herausforderungen bei Erstsemester-Studierenden der Informatik aufzudecken. In einer Pilotstudie an einer südafrikanischen Universität erstellten Studierende Traumzeichnungen und Narrative, die ihre akademischen Erfahrungen reflektierten. Die Analyse der visuellen und narrativen Daten identifizierte elf zentrale emotionale Hürden, darunter familiäre und finanzielle Belastungen, selbst auferlegte Erwartungen, Minderwertigkeitsgefühle und Stress im Zusammenhang mit Programmieraufgaben. Die Ergebnisse verdeutlichen die komplexe Wechselwirkung zwischen persönlichen und akademischen Lebensbereichen und betonen die Notwendigkeit, emotionale Barrieren proaktiv anzugehen. Der Artikel diskutiert die potenziellen pädagogischen Implikationen der DDD-Methodik und bietet Einblicke in deren Anwendung, um Lehrende dabei zu unterstützen, die emotionale und akademische Entwicklung ihrer Studierenden gezielt zu fördern.

Keywords: Bottleneck; Decoding the Disciplines; Disziplinäre Traum-Skizzen; Soziale Traum-Skizzen; Didaktik der Informatik

1 Introduction

Emotional challenges significantly impact student learning and success in higher education (Pekrun & Linnenbrink-Garcia, 2014; Middendorf et al., 2015). Students often encounter psychological barriers, such as anxiety, frustration, or a sense of inadequacy, that hinder their engagement and academic performance (Pekrun et al., 2002). Addressing these emotional bottlenecks is crucial for educators aiming to create supportive learning environments that promote deep understanding and retention of disciplinary knowledge.

The foundation of this work lies within the Decoding the Disciplines (DtD) framework (Pace, 2017). DtD is based on the premise that each academic discipline has its own unique ways of thinking and practicing that students need to master. The seven-step DtD framework provides a structured approach to identifying and addressing specific points where students' learning is interrupted (Middendorf & Shopkow, 2018). These points of interruption are referred to as bottlenecks. While bottlenecks can be cognitive or procedural, emotional bottlenecks (i. e., psychological barriers rooted in students' feelings and prior experiences) are equally significant yet often overlooked (Middendorf et al., 2015).

Emotional bottlenecks occur when students' pre-existing beliefs, emotions, or attitudes conflict with the demands of the subject matter or learning environment (Middendorf & Shopkow, 2018). In disciplines like Computer Science, which require rigorous problem-solving and abstract thinking, these emotional barriers can be particularly pronounced (Lahtinen et al., 2005). Students may experience feelings of overwhelm, fear of failure, or anxiety related to coding and technical challenges, leading to disengagement or resistance to learning.

Uncovering these emotional bottlenecks is a challenging task. Traditional pedagogical approaches may not effectively surface the underlying emotional issues that impede learning, as students might be unaware of them or hesitant to articulate their struggles (Mersky, 2022). Innovative methodologies are needed to access these hidden emotional landscapes to better support students in their academic journey.

This paper explores the use of a discipline-specific adaptation of Mersky's Social Dream-Drawing methodology (2013; 2022) as a tool to uncover the emotional bottlenecks experienced by students in Computer Science. By integrating this adapted methodology within the DtD framework, we aim to provide educators with a novel approach to identify and address the emotional challenges that students face. Through a pilot study conducted with first-year Computer Science students at a South African university, we investigate whether this innovative method can effectively reveal the emotional barriers that impact student learning. Our goal is to enhance educators' ability to foster a more positive and supportive learning environment, ultimately improving student engagement and success in the discipline.

2 Theoretical Framework

2.1 Emotional bottlenecks in learning

Emotional bottlenecks, also known as affective bottlenecks, are psychological barriers that hinder effective learning when students' prior beliefs, experiences, or emotions conflict with the demands of the subject matter or learning environment (Middendorf & Shopkow, 2018). These moments occur when students' pre-existing ideas clash with disciplinary constructs, leading to resistance or disengagement. This resistance can manifest as superficial participation, hostility, or even withdrawal from the course.

Middendorf et al. (2015) highlight that emotional bottlenecks are deeply intertwined with cognitive processes. Students' feelings about a particular issue are influenced by their cognitive understanding of it. For instance, contradictions between their preconceived notions and the discipline's requirements can evoke strong emotions like anger, confusion, or scepticism. Therefore, addressing emotional bottlenecks necessitates engaging with both the emotional responses and the underlying cognitive structures that support these emotions.

Within the DtD framework, emotional bottlenecks are significant obstacles that impede students' progression in learning disciplinary thinking (Pace, 2017). Educators are urged to decode not only the cognitive challenges but also the emotional responses that may block learning. These bottlenecks often stem from students' beliefs about their abilities or misconceptions about the subject matter, leading to a lack of motivation or active resistance (Middendorf et al., 2015). Unfortunately, educators may overlook these emotional barriers or remain unaware of them, exacerbating the problem.

Addressing emotional bottlenecks requires a strategic approach that combines cognitive and affective interventions. Step 5 of the DtD framework specifically focuses on motivating students to remain engaged despite emotional barriers (Middendorf & Shopkow, 2018; Pace, 2017). By creating a learning environment that acknowledges and addresses both emotional and cognitive aspects, educators can help students overcome these bottlenecks. This involves understanding the emotional dynamics at play and implementing strategies that meet students' affective needs, thereby encouraging deeper engagement with the subject matter.

2.2 Social Dream-Drawing

One promising methodology for identifying emotional bottlenecks in educational contexts is Mersky's Social Dream-Drawing (2013; 2022). Rooted in depth psychology and psychoanalysis, this approach is based on the belief that dreams are expressions of the collective unconscious (Mersky, 2022), offering insights into underlying emotions, perspectives, and psychological challenges. Originally utilised in therapeutic and organisational settings, Social Dream-Drawing has been adapted in educational research as a tool to give students a voice (Pule, 2024), to shed light on the challenges experienced by female academics (Barnard et al., 2023), and to explore students' real-life experiences (Alexander, 2023).

Mersky's approach (2008; 2013) involves the interpretation of actual or imaginary dreams through visual and narrative means. The methodology combines visual data (drawings) and narrative data (written or verbal descriptions) to uncover unconscious material, such as thoughts, emotions, and experiences that are typically inaccessible through conventional research methods. The drawings serve as a means of externalising internal conflicts and emotional responses that might otherwise remain hidden (Mersky, 2013).

At its core, Social Dream-Drawing offers a powerful way to understand how emotions and psychological states shape individuals' responses to their environment. As Mersky (2013) notes, the process of creating and reflecting on dream drawings allows participants to access a deeper understanding of their emotions and cognitive processes. In an educational setting, this methodology can be adapted to help uncover emotional bottlenecks that are often linked to students' resistance or struggles with specific disciplinary content (Middendorf et al., 2015; Pace, 2017).

One of the key strengths of the Social Dream-Drawing methodology is its ability to bring unconscious emotional responses to the surface. Visualising emotions through drawing can bypass the intellectual defences that often prevent individuals from confronting difficult emotions (Mersky, 2013). In educational contexts, where students may be reluctant or unable to articulate their emotional struggles, this methodology provides a creative and reflective outlet that can reveal deep-seated emotional bottlenecks.

Moreover, the collective aspect of the Social Dream-Drawing methodology, where participants share their drawings and narratives with peers, fosters a sense of shared experience and emotional validation (Mersky, 2013). This communal reflection can enhance understanding and empathy among participants, contributing to a supportive learning environment.

3 Methodology

In alignment with the DtD framework, this study proposes the Disciplinary Dream-Drawings (DDD) methodology as an adaptation of Mersky's Social Dream-Drawing (2013; 2022) for educational settings. The DDD methodology aims to explore the emotional challenges that students face in learning, particularly within the discipline of Computer Science. Rather than dealing with actual dreams, this approach uses the concept of dreams metaphorically to tap into students' unconscious thoughts and emotions about their academic experiences.

The DDD methodology involves collecting two types of data: visual data in the form of dream-drawings, and narrative data comprising written explanations and focus group discussions. Students are asked to create visual representations of their experiences as learners in Computer Science. These drawings, accompanied by brief narratives, provide a non-threatening means for students to express emotions such as fear, frustration, or anxiety, which may not be readily articulated through traditional methods.

3.1 Pilot study

A pilot study was conducted with first-year Computer Science students at a South African university to evaluate the effectiveness of the DDD methodology in uncovering emotional bottlenecks. During a scheduled contact session, 141 students were invited to participate. Each student received a blank A4 sheet of paper and shared coloured pencils. They were presented with the following scenario and instructions:

- Scenario: You have just woken up after dreaming about your current life as a Computer Science student.
- Instructions: Create a drawing of your dream.

Students were allotted 30 minutes for the drawing activity. Subsequently, they were given ten minutes to write a short description of their drawing on the reverse side of the paper. They were also informed that they could include their student number if they were interested in participating in further discussions, emphasising that submission was voluntary.

Out of the 141 students, 126 (89.4 %) submitted drawings, with 93 (66 %) expressing interest in further participation. The high response rate indicated that students found the activity engaging and were willing to share their experiences.

3.2 Initial data analysis

The initial analysis involved a thorough examination of each drawing and its accompanying narrative. Keywords and phrases were noted to identify recurring themes and specific challenges mentioned by the students. This process led to the identification of 21 broad categories of emotional challenges.

The drawings were then categorised into four groups:

- Future dreams: Depictions of students' aspirations unrelated to the given scenario (17 drawings).
- Positive experiences: Illustrations focusing solely on positive aspects, with no identifiable challenges (38 drawings).
- Challenges mentioned; No further participation: Drawings indicating challenges, but students did not opt for further involvement (19 drawings).
- Challenges mentioned; Interested in further participation: These drawings highlighted emotional challenges, and the students were willing to engage in focus group discussions (52 drawings).

In preparation for the focus groups, attention was concentrated on the fourth category. Although each drawing was unique, several drawings included visual elements such as loops, circles, and/or arrows to depict continuous cycles of tasks students had to repeat on a daily basis (see Figure 1). Another common theme was drawings that depicted the student's study space (see Figure 2). Watches or clocks were the single element that appeared most frequently in the drawings (as also seen in Figure 2). These common themes were further explored during the focus group discussions.

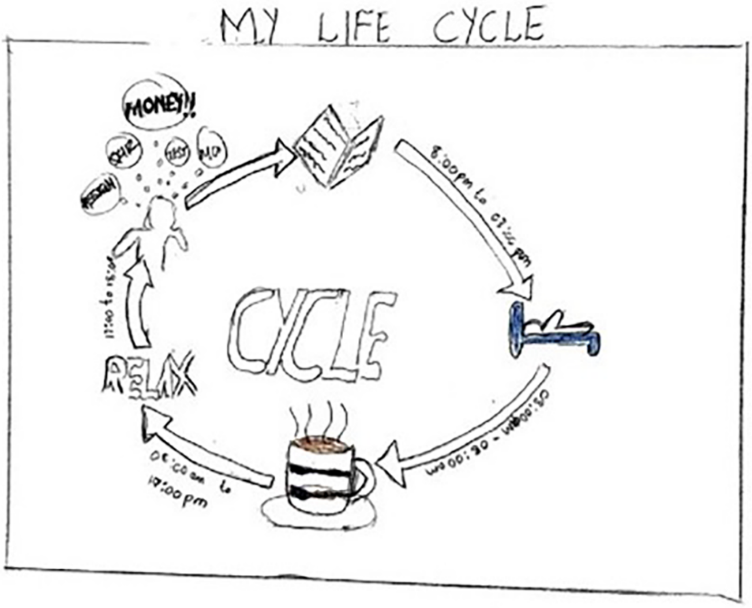

Figure 1: A dream-drawing portraying an endless loop of daily activities.

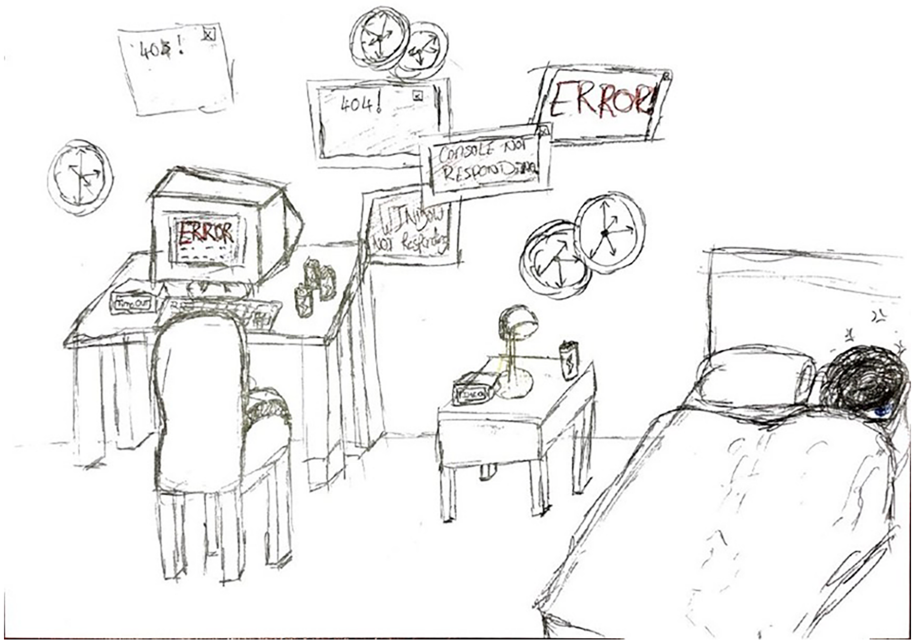

Figure 2: A dream-drawing portraying a study space overwhelmed by coding errors and ticking clocks.

3.3 Focus group discussions

Three focus group sessions were conducted, comprising a total of eleven participants. Sessions were scheduled based on students' availability, with group sizes ranging from one to seven participants. Each session followed the same structured procedure:

1. Introduction: Explanation of the session's purpose, ethical considerations, and obtaining informed consent.
2. Discussion of Drawings (repeated for each participant):
   - The participant (original drawer) presented their drawing and read their narrative.
   - Group members engaged in associative discussions, sharing interpretations and relating to the drawings.
   - The original drawer reflected on the feedback and shared further insights.
3. Thematic Exploration: Collective identification and discussion of emerging themes related to emotional challenges.
4. Reflection and Suggestions: As part of a general discussion, participants offered suggestions for improving emotional well-being and support within the Computer Science programme.
5. Conclusion: The facilitator summarised key points and closed the session.

All sessions were audio-recorded with participants' consent, and detailed notes were taken to capture non-verbal cues and group dynamics.

4 Findings: Identified Emotional Bottlenecks

Building upon the initial visual analysis, the focus group discussions in combination with the narrative descriptions allowed for a deeper exploration of the emotional bottlenecks experienced by the students. Eleven primary themes emerged:

1. Family pressure: Many students depicted scenarios where familial expectations exerted significant academic stress. The pressure to succeed, not only for themselves but also to fulfil their

family's aspirations, was a recurring theme. This burden often manifested as anxiety, particularly surrounding the fear of failing to meet these expectations.

2. Financial constraints: Financial concerns emerged as a major bottleneck. Students expressed worries about tuition fees, the cost of study materials, and the need to balance part-time employment with their studies. These financial pressures contributed to feelings of being overwhelmed and distracted, impeding their ability to fully engage with their academic work.
3. Sleep deprivation: A significant number of students included references to sleep (or the lack thereof) in their drawings (see Figure 2). The demands of their coursework often led to late nights and insufficient rest, negatively impacting their cognitive abilities and overall well-being.
4. Self-imposed pressure to perform: The expectation students placed on themselves to consistently achieve high academic standards was another dominant theme. This internal pressure often led to self-doubt and fear of failure, discouraging students from taking risks or participating actively in class.
5. Feelings of being overwhelmed: Many students conveyed a general sense of being inundated by the sheer volume of work and the complexity of the material. This was especially prevalent among those who felt they lacked the necessary background or foundational knowledge in Computer Science.
6. Mental health challenges: Issues such as anxiety and depression were frequently alluded to in both the drawings and discussions. These mental health challenges were often exacerbated by the stressors mentioned above, creating a vicious cycle that further impeded students' ability to cope with their academic responsibilities.
7. Reluctance to seek help: Despite the challenges they faced, many students were hesitant to ask for assistance. This reluctance stemmed from a fear of being judged as incompetent or not belonging in the academic environment. This is particularly concerning, as it suggests that students may be struggling in silence rather than seeking the support they need.
8. Feelings of inferiority: Some students expressed a sense of not being "good enough" compared to their peers. This often led to a reluctance to engage in group work or class discussions, further isolating them and reinforcing their feelings of inadequacy.
9. Procrastination as a coping mechanism: Several students interpreted their own procrastination as laziness, without recognising that it might be a coping strategy for underlying emotional or psychological stress. This misinterpretation often led to negative self-perception, further hindering their motivation and academic performance.
10. Overcommitment and time management Issues: Students reported having too many commitments, both academic and extracurricular. This overcommitment contributed to feelings of being overwhelmed and unable to manage their time effectively.
11. Stress related to coding activities: The technical challenges of coding were frequently highlighted as a source of stress. Many students felt that programming exercises were difficult and that they lacked sufficient support to navigate these challenges, leading to frustration and fear of failure.

These identified emotional bottlenecks have significant implications for students' learning experiences. The interplay between these factors often created a compounded effect, where one bottleneck intensified others. For instance, financial pressures could lead to increased working hours, resulting in sleep deprivation and reduced study time, thereby exacerbating feelings of being overwhelmed. Recognising and addressing these challenges is crucial for fostering a supportive learning environment.

5 Implications of the Findings

The emotional bottlenecks identified in this study have significant implications for how educators approach teaching and supporting students in disciplines such as Computer Science. The eleven bottlenecks (ranging from family and financial pressures to mental health challenges and stress related to coding activities) highlight the complex interplay between students' personal lives and their academic experiences. Addressing these bottlenecks is crucial for fostering a supportive learning environment that promotes student engagement and success.

Firstly, the prominence of family pressure and financial constraints suggests that many students are navigating substantial external expectations and socioeconomic challenges. These pressures can lead to heightened anxiety and stress, adversely affecting cognitive functions and academic performance. Educators and institutions can play a pivotal role by providing support resources, such as connecting students with financial aid services, scholarships, or bursaries, and facilitating open dialogues where students can discuss their challenges without stigma.

Moreover, issues related to sleep deprivation, overcommitment, and time management reflect students' struggles to balance academic demands with personal well-being. Chronic lack of sleep and overcommitment can impair learning and increase feelings of being overwhelmed. To address these concerns, educators should promote healthy habits by integrating time management and wellness workshops into the curriculum and encourage reasonable workloads to ensure that course demands are manageable and do not inadvertently encourage unhealthy study practices.

The internal pressures of self-imposed expectations, feelings of inferiority, and reluctance to seek help indicate a need for cultivating an inclusive and supportive classroom atmosphere. Educators can normalise the challenges associated with learning complex material by emphasising that difficulties are a normal part of the learning process. Encouraging help-seeking behaviour by making office hours welcoming and actively inviting students to ask questions can reduce the reluctance to seek assistance. Implementing peer support mechanisms, such as study groups or mentorship programmes, can also help students feel more connected and less isolated.

The prevalence of mental health challenges underscores the necessity for proactive measures to support students' well-being. Accessible mental health services should be readily available and promoted to students. Additionally, providing training for educators to recognise signs of mental distress and respond appropriately can create a more responsive support system within the academic environment.

Addressing the stress associated with coding activities highlights the need for pedagogical strategies that demystify programming and reduce anxiety. Educators can implement incremental learning by breaking down complex coding tasks into smaller, manageable components. Offering practical support through additional coding labs or tutoring sessions, and providing constructive and encouraging feedback, can build students' confidence and competence in programming.

These findings suggest that addressing emotional bottlenecks requires a holistic approach that integrates academic support with attention to students' emotional and psychological needs. By recognising and actively addressing these challenges, educators can enhance student engagement, improve learning outcomes, and promote the overall well-being of students. Institutions should develop policies and programmes that support diversity and inclusion, facilitate collaboration across disciplines to address emotional bottlenecks from multiple perspectives, and implement systems to regularly assess the effectiveness of interventions aimed at reducing these challenges.

6 Reflection on the Execution of the DDD Methodology

The execution of the DDD methodology during the pilot study provided valuable insights into its effectiveness as a tool for uncovering emotional bottlenecks in an educational setting. Firstly, it provided a structured yet flexible tool for identifying emotional challenges that impede student learning. By engaging students in a reflective process that combines visual and narrative data, the methodology allowed for the exploration of emotions that might remain inaccessible through conventional research methods. This aligns with the DtD framework's emphasis on addressing both cognitive and emotional barriers to learning (Pace, 2017).

Secondly, the collaborative nature of the methodology, particularly through focus group discussions, opened opportunities for students to articulate their emotional challenges in a supportive and non-judgemental environment. The sharing of drawings and narratives fostered a sense of shared experience and emotional validation among participants (Mersky, 2013). This communal reflection not only enhanced understanding and empathy but also contributed to a more inclusive classroom atmosphere.

Overall, the DDD methodology proved to be an effective and insightful approach for uncovering emotional bottlenecks among Computer Science students. By integrating this methodology into pedagogical practice, educators can better support their students' emotional and academic development. Following the insights gained from the pilot study, the guidelines outlined in Table 1 highlight several practical considerations for educators and researchers aiming to implement the DDD methodology in their own context.

Table 1: Guidelines for Implementing the Disciplinary Dream-Drawings Methodology

Component	Guidelines
Crafting the scenario	• Use an open-ended scenario to allow students to freely project their experiences. • Consider more specific scenarios to guide focus on particular academic aspects.
Materials and timing	• Provide adequate materials (e. g., individual sets of coloured pencils, ample paper) to facilitate creativity and expression. • Allocate sufficient time (e. g., 30 minutes for drawing, 10 minutes for writing) for deep engagement.
Facilitating focus group discussions	• Organise small groups of 4 to 6 participants to encourage participation and ensure a balance between diverse perspectives and individual sharing.
Venue for focus group discussions	• Choose a quiet, comfortable room separate from regular classrooms to foster a relaxed atmosphere. • Arrange seating in a circle to promote equality and encourage eye contact. • Provide equipment (e. g., large screen) to display drawings. • Minimise external distractions by attending to lighting and seating comfort.
Preparing probing questions	• Develop carefully crafted, tailored questions (for the general discussion step in the focus group discussions) based on preliminary analysis of drawings and narratives. • Aim to elicit deeper reflections and uncover underlying emotions and causes.
Ethical considerations	• Obtain informed consent and assure confidentiality. • Emphasise voluntary participation. • Create a safe environment due to the sensitive nature of emotions being explored.
Emotional support	• Provide access to counselling services or support resources to assist participants who may experience distress during or after the activity.
Cultural sensitivity	• Given the diverse backgrounds of students, cultural considerations should be taken into account when interpreting drawings and facilitating discussions. • Be mindful of different modes of expression and potential cultural stigmas around discussing emotions.

7 Conclusion

The proposed Disciplinary Dream-Drawings (DDD) methodology, adapted from Mersky's Social Dream-Drawing method (2008; 2013; 2022), has proven to be an effective and innovative tool for uncovering the emotional bottlenecks experienced by first-year Computer Science students. By engaging students in a creative and reflective process, the study illuminated a range of emotional challenges (such as family and financial pressures, self-imposed expectations, feelings of inferiority, and stress related to coding activities) that significantly impact their learning experiences and academic performance.

The findings underscore the complex interplay between students' personal lives and academic responsibilities, highlighting the necessity for educators to address not only cognitive but also emotional barriers to learning. The emotional bottlenecks identified are multifaceted and deeply intertwined with both personal and academic spheres, affecting students' motivation, engagement, and overall well-being.

Implementing the DDD methodology has important pedagogical implications. It offers educators a structured approach to identify and address emotional challenges, fostering a more supportive and inclusive learning environment. By integrating this methodology within the DtD framework (Pace, 2017), educators can develop targeted interventions that acknowledge and alleviate emotional barriers, ultimately enhancing student engagement and success.

Reflecting on the execution of the DDD methodology reveals its potential to transform teaching practices. The process of creating and discussing dream-drawings not only provides valuable insights into students' emotional landscapes but also encourages open communication and shared understanding within the classroom. The collaborative nature of the methodology fosters a sense of community and emotional validation, which can alleviate feelings of isolation and reluctance to seek help (Mersky, 2022).

In conclusion, addressing emotional bottlenecks proactively is crucial for fostering an educational experience that empowers students both academically and personally. Educators and institutions have a responsibility to create learning environments that not only impart knowledge but also support the emotional and psychological well-being of their students. By embracing innovative methodologies like the DDD, we can better support our students' holistic development, promote inclusivity, and enhance learning outcomes. Future research could explore the application of the DDD methodology across different disciplines and educational contexts, further contributing to our understanding of how to effectively address emotional challenges in higher education.

Statements on ethics and conflict of interest

Ethical clearance for this study was obtained from the General/Human Research Ethics Committee of the University of the Free State prior to the study (Ethical Clearance number: UFS-HSD2023/0161). All participants provided informed consent, and their participation was voluntary. Participants were free to withdraw from the study at any stage without facing any negative consequences. This work is based on the research supported by the South African National Research Foundation. The author declares that there is no conflict of interest associated with this research.

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