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Digital Technologies and Calculus: Students' Peaks and Pits

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Abstract

Understanding calculus students' perspectives can provide valuable insights into their learning needs and help develop strategies to enhance persistence in STEM programs. Numerous studies have shown that the use of digital technologies (DT) influences student engagement, motivation, and mathematics achievement. In this project, we explored students' perspectives on using DT in calculus. We interviewed eight calculus students from a midwestern doctorate-granting institution in the United States and used thematic analysis informed by the didactical tetrahedron, accounting for internal and external factors that may influence the teaching and learning process. Students reflected on their use of technology, identifying various benefits, including looking for similar problems, checking their work, and visualizing concepts. They also identified challenges, particularly with online feedback. Additionally, students shared their perceptions of how instructors utilized DT in calculus, recognizing benefits when they provided relevant course material or solved mathematical problems, and highlighted challenges related to the misalignment between course content and online homework. Finally, students described how external factors, such as classroom environments, facilities, and accessibility, impacted their use of technology. These findings offer valuable insights for faculty and institutions regarding effective DT implementation and highlight the importance of considering the specific instructional context in calculus courses.

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Introduction

Given the pivotal role of calculus in STEM retention (Ellis et al., 2016; Rasmussen & Ellis, 2013; Riegle-Crumb et al., 2019; Sithole et al., 2017), there has been growing interest among United States (US) institutions to investigate the teaching and learning of calculus. Recent research in calculus education has focused on examining how students learn calculus concepts and on understanding teachers' knowledge, beliefs, and practices (Bressoud et al., 2016; Rasmussen et al., 2014). Despite numerous individual and coordinated efforts to support students' learning experiences in calculus classes, students continue to retain misconceptions and struggle with the conceptual understanding of limits, derivatives, and integrals (e.g., Blaisdell, 2012; Bezuidenhout, 2001; Carlson et al., 2003; Denbel, 2014; Habre & Abboud, 2006; Hall, 2010; Orhun, 2012; Rasslan & Tall, 2002; Sealey, 2014; Serhan, 2015; Thompson, 1994; Wagner, 2018).

Extensive scholarly literature highlights the potential of using digital technologies (DT) to enhance mathematics learning and student motivation (Drijvers & Sinclair, 2024; Higgins et al., 2019). Nonetheless, the mere presence of technology does not guarantee an enhancement in students' learning and motivation (Cohen et al., 2003). Regarding the teaching and learning of calculus, numerous studies have focused on leveraging specific technological tools like GeoGebra or Desmos and sophisticated computer algebra systems (CAS) to foster students' conceptual understanding, visualization skills, and mathematical representation (e.g., Hunter, 2011; Takači et al., 2015; Yu, 2023). Less research has focused on understanding students' perspectives regarding technology integration within calculus classes (e.g., Boz & Adnan, 2017; Esparza Puga & Sánchez Aguilar, 2021; Sevimli, 2016). These studies have focused on the students' perspectives about specific DT such as YouTube or CAS (e.g., Esparza Puga & Sánchez Aguilar, 2021; Sevimli, 2016) and have included the perspectives of college students from different courses rather than focusing exclusively on calculus courses (e.g., Esparza Puga & Sánchez Aguilar, 2021), or only consider a specific subpopulation of students such as engineering majors (e.g., Boz & Adnan, 2017). Though some studies focus on specific technologies, we could not find any studies that explore students' perspectives on the overall use of DT in calculus courses.

Investigating students' perspectives can provide valuable insights into their experiences and help design targeted strategies to overcome challenges. Additionally, there is a significant relationship between students' perspectives, their mathematics achievement, and their motivation for learning (Muis, 2004). Understanding these perspectives is essential for creating a meaningful and impactful learning experience in calculus classes.

This gap in the literature prompts an exploration of students' perspectives on the general use of technology, aiming to acknowledge their concerns, preferences, and recommendations. Such insights hold significant promise for guiding instructors in anticipating and addressing students' apprehensions, thereby fostering a more supportive and effective learning environment for calculus classes. Thus, the primary objective of this study is not to determine the extent of technology usage or which technologies students use but rather to consider students' perceptions of the effective use of technology to enhance the teaching and learning of calculus.

The research questions that guide our study are:

(1) How do students perceive the benefit of using technology in calculus classes?
(2) What challenges do students face when using technology in calculus classes?

Digital Technology

We refer to DT as any technology that supports, facilitates, and enhances mathematical learning processes, including hardware, software, and digital resources. Crisan et al. (2023) classify mathematics education technology as digital technology devices, applications (apps), and tools. They also specify whether apps and tools are generic or specific for teaching or learning mathematics. In this paper, we refer to generic DT apps and tools and mathematics–specific DT apps and tools. The generic DT apps and tools category compiles all apps and tools that enable mathematics communication through reading or writing (Crisan et al., 2023), such as PowerPoint, PDF notes, Blackboard, Zoom, and e-books. Mathematics–specific DT apps and tools are used to support, enhance, and facilitate the learning and teaching of mathematics (Crisan et al., 2023). While the generic DT apps can present content, we consider mathematics–specific apps and tools created to learn and teach mathematics–related content, such as calculators or graphing software.

We are interested in the benefits or challenges perceived by calculus students when interacting with generic or mathematics-specific DT apps and tools in the following ways: (1) as tools used by students to learn course content, (2) as mediums utilized by instructors to teach, share class material, or assess students, or (3) as a means for students to communicate with instructors regarding course content. However, the mere presence of technology, without its use as described above or without explicit interaction with it for learning, falls outside the scope of our study.

Literature Review

In this section, we build on existing literature concerning the integration of DT in calculus classes. The students' use of online resources in mathematics classes has been studied at the college level (e.g., Gueudet & Pepin, 2016; Pepin & Kock, 2021). Pepin and Kock (2021) explain that students who are more advanced in their undergraduate degrees use mathematics DT tools such as Mathlab, Simulink, and JavaScript to solve mathematical questions in their courses. Regarding calculus courses, the effective integration of DT enhances conceptual understanding through visualization, multiple representations, and exploration of key calculus concepts like limits, derivatives, and integrals (e.g., Bressoud et al., 2016; Ferrara et al., 2006; Rasslan & Tall, 2002). To delve deeper into the utilization of technology in calculus classes, we explore relevant literature addressing efforts to improve the teaching and learning of calculus by examining both the instructors' and students' use of technology (Drijvers, 2015; Ferrara et al., 2006; Takači et al., 2015).

Instructors Using Technology in Calculus Classes

Calculus instructors utilize DT for several purposes, primarily to introduce or explore calculus concepts. Examples of class activities incorporating DT have been extensively shared as resources for other teachers to implement in their classrooms (e.g., Hohenwarter et al., 2008; Liang, 2016; Yu, 2023). For example, Yu (2023) used Desmos, an advanced graphing calculator, to create an animation of the rate of change concept to help students who were not necessarily familiar with Desmos understand its relationship with derivatives. Other instructors have used technology to share class materials (e.g., Maciejewski, 2016). Maciejewski (2016) found that using online videos in a flipped calculus teaching model increased student performance and understanding of calculus.

Research on how instructors perceive DT has been studied at the school level. Researchers have found that school teachers are not confident in their proficiency in using mathematics-specific DT that are new to them and are concerned regarding accessibility, lack of training, and lack of alignment with the curriculum (e.g., Hudson et al., 2008; Muhazir & Retnawati, 2020; Sacristán, 2017). Less research has focused on instructors' use and perspectives of mathematics-specific DT at the calculus college level (e.g., Martínez-Planell et al., 2023; Serkan, 2013; VanDieren et al., 2020). Martínez-Planell et al. (2023) found that calculus instructors use the dynamic Java applet CalcPlot3D for teaching multivariable calculus, and they perceive these DT help students visualize multivariable calculus concepts and are convinced this will help with building conceptual understanding. Additionally, Serkan (2013) found that instructors use DT to facilitate students discovering and solving calculus problems. They also reported difficulties using DT. Specifically, they perceived its use as distracting and were skeptical of using it when students had not yet mastered basic mathematical skills and concepts.

Extensive research has examined students' perceptions of instructors' use of DT for teaching calculus. However, they have focused on using generic DT apps and tools and have found that students have positive experiences with this type of DT in their calculus courses (Loch, 2005; Othman et al., 2017; Vajravelu & Muhs, 2016). For example, Othman et al. (2017) found that most students perceived as positive the use of PowerPoint as considering mobility and learning satisfaction. Some research has examined how the use of DT impacts calculus students' attitudes toward mathematics (e.g., Sonnert et al., 2014). We also found limited research examining students' perception of instructor use of mathematics DT apps and tools (Bedada & Machaba, 2022). Bedada and Machaba (2022) found that students liked learning calculus using GeoGebra classroom-oriented approaches. Specifically, this quantitative study found that students agreed that scaffolding activities offered better learning opportunities than traditional classroom ones.

Students Using Technology in Calculus Classes

Researchers have examined how the use of different DT can benefit calculus students' learning experiences and how the use of DT can support the doing of mathematics by doing quick arithmetic computations or visualizing concepts (e.g., Hunter, 2011; Takači et al., 2015). Using DT enhances learning (e.g., Hunter, 2011; Takači et al., 2015). Hunter (2011) investigated the impact of graphing calculators on calculus students' reasoning in solving problems on definite integrals and their applications and found that using graphing calculators was more effective in monitoring progress than traditional methods without graphing calculators. Takači et al. (2015) conducted a study that compared two groups of calculus students in a collaborative environment while examining functions and drawing their graphs. One group used GeoGebra as a tool, and the other completed the task without using it. The results showed that the students who used GeoGebra had higher scores in the calculus post-test.

Extensive research has explored the use of DT to assist with visualizing concepts (Nongharnpituk et al., 2022; Takači et al., 2015), getting immediate feedback (Dorko, 2020; Lampe & White, 2023), and seeing similar examples (Dorko, 2021; Esparza Puga & Sánchez Aguilar, 2021). For example, some DT facilitate the visualization of mathematical concepts by allowing multiple representations, thus enhancing a complete visualization of calculus concepts (e.g., Nongharnpituk et al., 2022; Takači et al., 2015). Dorko (2021) discusses that students use similar examples to troubleshoot, to check if they are on the right track, and to see the form of the answer. Dorko (2020) discusses how online homework provides intermediate feedback, allowing students to work on multiple homework trials when they get an incorrect answer.

In mathematics college courses, Ní Shé (2023) conducted a meta-analysis and reported that accessibility issues of DT may be explained by the lack of familiarity, financial limitations, and ability to find DT resources. We did not find studies examining these specific limitations in calculus courses. While extensive research has examined the uses of technology and its benefits to teaching calculus, few studies have focused on students' perspectives on using technology in calculus courses.

Some studies have focused on how students perceive the use of technology (Lampe & White, 2023; Nongharnpituk et al., 2022; Pepin & Kock, 2019; Sevimli, 2016). Lampe and White (2023) found that calculus students like online homework because they find it accessible and adaptable and can get immediate feedback compared to written homework; however, students also share that online homework does not allow them to keep track of their progress. Nongharnpituk et al. (2022) found that future teachers in a calculus class perceived the use of GeoGebra as a tool for providing visualization and conceptual understanding. Sevimli (2016) found that calculus students with an analytical thinking style were likelier to limit CAS use than those with more visual thinking skills. Additionally, students who used CAS developed a stronger preference for conceptual understanding, while those who did not tended to favor procedural understanding. Pepin and Kock (2019) examined the use of resources in calculus and linear algebra. While focusing on resources for learning calculus, they found that students reported using digital resources such as YouTube and Khan Academy.

Many of the existing studies are narrowly focused on specific digital tools, such as online homework systems, Geogebra, or CAS (Lampe & White, 2023; Nongharnpituk et al., 2022; Sevimli, 2016), while others take a broader, more inclusive approach to the use of digital resources (Pepin & Kock, 2019). As these studies do not examine students' perspectives on the overall use of DT in the context of calculus learning, this exposes a gap in the literature. A more comprehensive examination is needed to fully capture how students engage with and perceive DT in calculus education.

Theoretical Perspective

To shed light on our investigation, we draw from the didactical tetrahedron perspective. The didactical tetrahedron is an extension of the instructional triangle, which considers the interaction among student, teacher, and mathematical concepts and adds an extra vertex to include technology (e.g., Olive et al., 2009; Tall, 1986). The tetrahedron redefines the learning space where mathematical knowledge emerges by considering how mathematics interacts with teachers, students, and technology. Our research is rooted in analyzing the faces of this tetrahedron, and we enclose a tetrahedron inside a sphere to represent the context. Tall (1986) first proposed the idea of a tetrahedron inside a sphere and considered the context of using inquiry and cooperation as components that contribute to students' learning with technology.

The didactical tetrahedron has four vertices representing the learner, the teacher, the mathematics content, and the technology. As an extension of the didactic triangle, the idea expands on the interactions among these four vertices for emerging mathematical knowledge and practices (Olive et al., 2009). Tall (1986) used the vertices of pupils, teachers, content, and computers in an enhanced Socratic mode, starting with a demonstration on one computer to show students a concept followed by teacher and pupil discussion, encouraging cooperation in a whole group setting. Tall illustrated the context of these classroom practices as a sphere enclosing the tetrahedron.

The idea of including technology as one of the tetrahedron's vertices has been developed further in studies like Olive et al. (2009), which positioned students, teachers, tasks, and technology as vertices. They also emphasize using faces as a lens to illustrate the possible inter-relationships among the four vertices.

Our Study: Didactical Tetrahedron in a Sphere

In our study, we adapted the didactical tetrahedron, as shown in Figure 1, to have four vertices—calculus content, instructors, students, and DT (CIST)—that form four faces: calculus content, instructor, and DT (CIT); calculus content, students, and DT (CST); instructor, students, DT (IST); and calculus content, instructor, students (CIS).

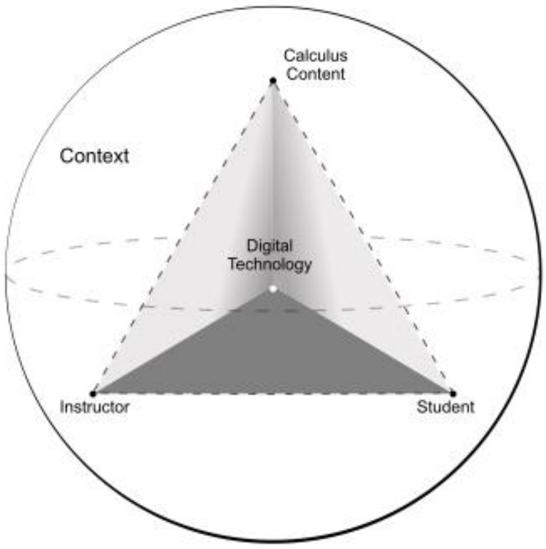

Figure 1. Calculus Content, DT, Instructor, Student (CIST) Didactical Tetrahedron in a Sphere

We kept the idea of using student, teacher, content, and technology, but we modified these to ensure alignment in our study. First, following Crisan et al. (2023), we use DT to disambiguate the term technology. We also refer to the calculus content to emphasize what we mean by content. Using instructors instead of teachers is not related to classroom practice but to a typical language to refer to a college educator. The word *instructor* includes professors, part-time and full-time instructors, and graduate teaching assistants who may teach calculus.

As we need to analyze three vertices to visualize the interrelationships among one face, let us start by considering two vertices: the calculus content and the DT. DT can be used as generic tools to deliver calculus content (Crisan et al., 2023), which serves as a mediator, or as a mathematics–specific tool (Crisan et al., 2023) to facilitate visualization and manipulation. The CIT face shows up when instructors use technology to teach calculus content, influencing the student learning experience. This includes, for example, an instructor using technology to solve a problem in class, selecting problems on a computer for homework, and sharing course materials.

While these scenarios would only make sense with the presence of students, students play a secondary role as they do not interact directly in this triangle. In this scenario, students may or may not engage in the graphing software activity shown by the instructor. If, in this scenario, the student is the one utilizing the graphing software to learn calculus content, that is a moment when the CST face will show up.

Let us now consider the vertices of the student and the instructor. Without content to teach or learn, the student-instructor interaction is just an interaction between two human beings. When adding DT to this relationship, it works as a mediator of this relationship to facilitate communication to discuss course content. For example, a virtual office hour or an email exchange represents the IST face, where the student seeks help to understand specific class content. This is indeed an example of the CIST didactical tetrahedron in action. The instructor-student relationship with the content and without DT, CIS face, would be the traditional didactic triangle. In other words, when considering this face, DT does not play a central role in the didactic process as in a discussion between teachers and students about content. The DT might be present in the background to support the discussions, such as a presentation, but in this case, the content plays the main role in producing those discussions. Since the CIS face did not provide insights to address our research questions and was not a result gained from our interview questions, it will not be included in this investigation.

Methods

Eight calculus students volunteered to participate in this study. At the beginning of the spring 2023 semester, the students completed a demographic survey and were interviewed during the subsequent summer. The audio of the interviews was recorded, transcribed, and then de-identified for analysis.

Research Context

This study was conducted at a US midwestern PhD-granting institution serving approximately 15,000 students. Around 400 students take calculus per the 14-week semester, and roughly half are from the College of Engineering and Engineering Technology. The remaining students belong to the Colleges of Liberal Arts and Sciences, Business, Education, and Health and Human Sciences.

Calculus classes are coordinated. This coordination consists of common midterm and final exams, common online homework, and the optional implementation of collaborative group work at least once a week to complete weekly worksheets, which act like written homework. Calculus classrooms usually have a computer, a projector, a whiteboard, a webcam, and a traditional lecture setup consisting of rows and fixed seating. When the study was conducted, instructors were encouraged but not required to have small group activities once a week, and the Department of Mathematics transitioned to open resources for textbooks and online homework in calculus classes.

Participants

Eight calculus students consented to participate in this study and completed a survey at the beginning of the Spring 2023 semester to collect demographic information. The reference number for this study is HS23_0150, approved by the Institutional Review Board. During the subsequent summer, the participants took part in follow-up interviews. In this study, we report on their responses during the follow-up interviews. We assigned pseudonyms to participants to protect their identities.

Alejandro was a sophomore first-generation student from the Department of Computer Science enrolled in Calculus I and reported having financial struggles, a part-time job, and a long commute. Bria was a junior first-generation student from the College of Engineering enrolled in Calculus III and reported having transportation issues, financial struggles, and a part-time job. Diana was a senior first-generation student from the School of Music in the mathematics teaching preparation program and reported having a part-time job and a long commute. Grace was a sophomore student from the College of Engineering enrolled in Calculus III and reported having financial struggles and a part-time job. José was a sophomore transfer student from the Department of Earth, Atmosphere, and Environment enrolled in Calculus II and reported having financial struggles. Nathan was a sophomore student from the College of Engineering enrolled in Calculus III. Said was a sophomore student from the Department of Computer Science enrolled in Calculus II and reported having a long commute. Sarah was a sophomore transfer student from the College of Engineering enrolled in Calculus I and reported having a full-time job and a long commute.

Data Collection

We collected data through a demographic survey and one individual semi-structured one-hour interview. Students in all Calculus I, II, and III courses completed the demographic survey within the first four weeks of the Spring 2023 semester. The demographic survey questions are included in the appendix. Each student had three points added to their total point value on the first exam as an incentive to complete it. We strategically selected students to conduct the interviews in ways that students were enrolled in different calculus sections and be representative of all three calculus sequence sections. The eight students who agreed to meet via Zoom during the subsequent summer received a $25 Amazon gift card as compensation.

The first and second authors conducted four interviews each. The interview questions focused on documenting students' perspectives about using technology in the teaching and learning of calculus. We asked participants about the type of technology that they used to learn calculus, the type of technology they would like to see in the instruction of calculus, and their perspectives about the benefits, if any, of using technology in calculus classes. We also asked questions about their experiences with assessments and their suggestions for having an ideal calculus classroom to teach and learn mathematics. The interview questions are included in the appendix.

Data Analysis

The semi-structured interviews were conducted via Zoom, audio recorded, and transcribed for analysis. To ensure the confidentiality of participants, we then de-identified the data by assigning pseudonyms. We used thematic analysis to analyze the data (Braun & Clarke, 2012). The three authors read the transcripts of four interviews separately to familiarize themselves with the data and generate initial codes (Saldaña, 2021).

The initial codes in the data were related to the type and use of technology reported by students. The authors met to discuss the initial codes, analyze the proposed codes, refine existing ones, and introduce new ones. The final codebook was framed on the interactions that resulted from the four faces of the CIST didactical tetrahedron. The three authors then used the final codebook to code the eight interviews and met until a 100% consensus was reached. The agreement of the coding was recorded using MAXQDA during weekly meetings.

Results

While asking questions about technology, students described their experiences using DT in calculus classes. We framed their responses using the faces of the didactic tetrahedron. Specifically, we found broader mentions of the CST and CIT faces. The IST face is the CIST didactical tetrahedron, as all the interactions in this face were explicitly related to calculus content. We finalize this section by reporting on factors related to the sphere, which provides insights into the classroom context when using DT.

The CST Face

For the calculus content, students, and DT (CST) face, we report on activities where students interact with both technology and calculus content, aiming to learn the course material. As shown in Table 1, students discussed CST interactions in their calculus classes by reviewing concepts, visualizing or exploring calculus content, doing online homework, looking for similar examples, checking work, and speeding up the process.

Table 1. Participants Who Mentioned the CST Face

The CST Face	Participants
Reviewing concepts	Alejandro, Bria, Diana, Georgia, José, Nathan, Said, Sarah
Visualizing and exploring calculus content	Bria, Diana, Georgia, José, Nathan, Said, Sarah
Doing online homework	Alejandro, Bria, Georgia, José, Sarah
Looking for similar examples	Alejandro, Diana, Georgia, José, Sarah
Checking work	Bria, Diana, José, Nathan, Said
Speeding up process	Alejandro, Diana, José, Nathan, Said

Reviewing Concepts

Students' most common use of DT was for reviewing concepts. For example, they used it to review notes when they missed classes and needed to catch up or to understand concepts they were learning in class. Some participants found that DT helped them review calculus concepts when they did not attend a class or struggled to understand a concept. For example, Sarah noted:

> It [DT] gives me more time or more options if I can't make it to class that day, or if I just need extra time to the class than provided. I can sit and review, or even go online and just even look up videos or if there's a link in class to expound on an idea until I can understand it fully.

Sarah explained that DT provides access to content even when she cannot attend classes. In class, Sarah used webpage links likely shared by her instructor. Additionally, Sarah searched for videos to understand the concepts she struggled with in class or did not understand well because she could not attend class. Sarah shows persistence in understanding the calculus concepts and perceives DT as a good resource, as they provide "more time or more options" for reviewing concepts.

Students also used DT to review class content, even when attending classes. This was commonly done by reviewing instructors' online notes or watching videos. For example, when solving a calculus problem, José used different resources:

> I would watch YouTube a lot for like a lot of my topics and then kind of just see how they work through the problem. And then if I'm still lost or I want further clarification that I'm not able to ask the YouTuber, right? Then I would go to the tutoring center, or even if it's a quick question, I'll ask at the end of my math class to my instructor.

By using different resources, José acknowledges DT as a preferred resource, however, it has its limitations as one cannot ask one-on-one questions to the YouTuber. The preference for using DT as a first resource when having a question was a typical response from other students. Despite the students being aware of different resources like their instructor or the learning center, they found DT was convenient as a first step when struggling with a calculus problem.

Visualizing and Exploring Calculus Content

Seven students mentioned that DT were useful for visualizing or exploring concepts. Calculus students explained that dynamic mathematics software like CalcPlot3D and Desmos facilitated both visualization and exploration of calculus content. For example, José explained the usefulness of a three-dimensional system like CalcPlot3D:

> If I'm doing a problem and I'm kind of confused on how it's really working out, I can put it on my 3D plot and say "Oh, okay, I see this shape, so now this makes sense. So the surface does make sense, and what I'm finding, and my limit bound should be." and then it kind of helps us tie everything together.

On this note, the visual representation José used not only clarified his confusion but also provided a concrete way to connect the surface of the graph to its limit bound. The dynamic software serves as a powerful tool, enabling the student to explore relationships between variables and reinforcing the importance of visualization in understanding calculus concepts. Such insights underscore how integrating DT can foster a more robust conceptual understanding, especially when students face challenges in traditional problem-solving approaches.

Doing Online Homework

Students highlighted issues in the process of doing calculus online homework. Specifically, students expressed concerns regarding the feedback provided in online assessments, identifying it as a significant issue in their learning experience. The feedback typically lacks the detail necessary for meaningful understanding, hindering their ability to grasp calculus concepts effectively. For example, Bria noted:

> I feel like I've put way more effort into math when technology is used versus, like, a professor like you, and a professor doing a one-on-one, or when a professor is lecturing in the class and is telling you, like, "You're here and you're seeing it real-time. Okay, this step is this step because of this." You know what I'm saying? Versus a computer giving you a big fat red X, like, "No, that's not right." And even if they do give you steps, I don't know. It just doesn't work out for me. Yeah, it just doesn't work out for me.

Bria's remarks underscore a critical distinction between traditional instructional methods and technology-enhanced learning. While technology can facilitate engagement, the lack of personalized feedback diminishes its effectiveness. Bria, like other students, expresses a preference for real-time guidance from instructors, emphasizing the importance of understanding each step in the problem-solving process rather than simply receiving feedback on whether the answers are correct or incorrect when completing online homework. This reveals a deeper need for formative feedback that addresses the cognitive processes involved in mathematics. Without such support, students feel frustrated and disconnected, highlighting the necessity for DT to not only assess correctness but also to nurture a more comprehensive understanding of calculus concepts.

Looking for Similar Examples

Students mentioned going online and browsing similar examples so they could use them as resources for learning course content. Diana noted:

> I'll also google the problem and see if there's similar problems that pop up and see how other people on the internet solved them. Although it's just people on the internet so I don't know if I can trust that. I do look sometimes if I really don't understand a problem, I go to Google as my last resource.

Here, Diana used similar examples online as a resource but is aware of the limitations regarding the accuracy of the approaches and solutions seen online. This shows that Diana used her understanding of calculus concepts to solve problems but may look for ideas and approaches while solving them. Students also discussed wanting to have examples to see step by step solutions and mentioned this could be created or provided by the instructor by posting these solutions online. This practice showed students value the use of learning management systems for accessing similar examples that can support them when struggling with a concept. For example, when discussing how DT could be good for the calculus learning experience, José noted:

> It would be nice if, like, you know, not every instructor has to do this, but maybe just the math department where they went through all the lessons and just hand-wrote all the answers, like working through the problem, and then kind of just uploaded that to Blackboard. [...] So it would be nice to say, okay, I stumbled, I'm stuck, I can look online, see how they've been through it, get it right, and then keep it moving.

José's comments, in particular, underscore a reliance on such examples for self-directed learning. His reference to being "stumbled" or "stuck" reveals a critical moment in the learning process where immediate access to similar problems can serve as a form of academic support. This reliance on online resources reflects a broader trend where students are increasingly turning to digital platforms to resolve cognitive obstacles independently.

Checking Work

Students mentioned using DT to check their work. Specifically, they discussed using graphing software or Chegg to check if their graphs were accurate or the correctness of their solutions. For example, Said noted:

> When I was going through homework and things like that, I was building the graph on the application, and then I was kind of converting it over doing the work in person as well to kind of help me through just to kind of double check my work and verify that I was building the right graph.

Said's use of graphing software illustrates how DT can support learning by allowing students to visualize concepts while working on homework. By transitioning from the application to manual graphing, Said uses DT as a complementary resource to check accuracy, thereby enhancing his understanding through constructive feedback.

Speeding Up Process

Students discussed using DT as a good support for computing simple calculations. For example, Nathan explains that using this resource helped him to "speed it up and even take on more complicated problems." Another student, Diana, explained this further:

> Instead of spending all my time multiplying and dividing and adding in my head or on the paper I could just do it in the calculator and know that the way the process that I took to get there was what I spent the most time on, if that makes sense. So it felt like I was allocating more time [to] learning the material than computing because of the calculator.

Diana's positive perspective about using DT in calculus classes relies on allowing time and energy to learn the calculus content rather than redoing arithmetic computations. This shows how DT can shift the focus from manual computation to deeper engagement with the problem-solving process and understanding of calculus concepts.

The CIT Face

The calculus content, instructor, and DT (CIT) face highlights how students perceive the instructors' interaction with both technology and calculus content, shaping the overall learning experience and influencing their understanding of the course material. The results of this face are shown in Table 2. Students reported instructors sharing course materials, doing mathematics, and selecting online homework problems.

Table 2. Participants Who Mentioned the CIT Face

The CIT Face	**Participants**
Instructors sharing course materials	Bria, Georgia, Nathan, Said
Instructors selecting online homework problems	Bria, José, Said
Instructors doing mathematics	Diana, José, Nathan

Instructors Sharing Course Materials

A common student perception of how instructors use DT was as a tool for sharing course materials with them. Students reported their instructors posted materials online or used DT to teach in the classroom. For example, Said noted, “So, the material that we had for the class was mostly posted online through Blackboard.” In this note, Said explains the instructor used Blackboard to share class materials such as notes and worksheets. Said explains how this instructor’s practice helped with reviewing concepts:

> [...] If you didn't understand a certain topic and you felt like you could use a little bit more help or a little more practice on that problem, you could go back into the notes, see how he would approach and how he did a certain problem.

This shows that instructors sharing course materials helped students learn calculus concepts. Said used these posted materials when he needed help understanding a topic or to practice problems.

Additionally, other students highlighted that instructors use DT for teaching. These included using a projector, incomplete notes to fill in class, and presentation software. For example, Bria mentioned: “she [the instructor] will also upload the PowerPoint as well as the notes.” This is a way Bria’s instructor was using presentation software. However, the use of presentation software limited Bria to follow the class explanations while attending class:

> [The instructor] tried to do the PowerPoint one day, like really clicking through the slides, and it was horrible. Like, it was, it was horrible, because there was no, like, working out any example for us or anything. It was just like the steps, but you know sometimes in math, each step sometimes has a step, kind of in between.

Bria explains that using slides for teaching calculus classes might not be ideal as it provides a fixed setting to focus on only one solution, and it does not show all the steps. What Bria describes is a perception of a teacher-centered practice where students are probably less active in providing strategies for solving the calculus problems, and the instructor is just “clicking through the slides” to present their solution.

Instructors Selecting Online Homework Problems

Students referred to working on problems that lacked alignment with what they were learning in their calculus classes. This aligns with the CIT face as these were choices from their instructors while using DT to assess calculus content. For example, Said noted, “Some questions weren't taking the approach of what the teacher may have taught us in class.” Another student, José, noted:

> We do online homework and some of the lessons where it's like the, like, partial derivatives. It's like finding volumes and stuff like that. He would do homework where like a word problem, like one question out of the 10. And that last one, I'm just like, just writing it and I was like, “Why is this word problem in here?” I don't know. Honestly, I'm really, I've never been the biggest fan of the word problems. I do think they can be good, but I also will say that in the test, he does not use word problems at all.

Said and José discuss a disconnection between the type of problems taught in class and the concepts assessed in the online homework. While José acknowledges the potential value of word problems, his frustration is rooted in the inconsistency in class and homework.

Instructors Doing Mathematics

Students perceived DT as useful for doing mathematics. In this case, students described how instructors used dynamic software like Desmos, three-dimensional software, and Wolfram Alpha to solve mathematical problems in class. Diana exemplifies this:

> I had never used Desmos before college or even before last academic year. I had never known that Desmos existed. But then our teacher in Calc 2 last spring showed us Desmos and I was like, “Oh, this is really cool!” And I liked using that. I'm really glad I found that resource. I actually use it all the time now. And it's good for teaching too. And Wolfram Alpha, my Calc I professor showed us Wolfram Alpha if we ever needed help with the problem. Or if we wanted to learn more about a problem we could plug it into Wolfram Alpha. And I thought that was really cool. I still use it.

Diana, who is also a future teacher, appreciated the teacher working through problems using Desmos and Wolfram Alpha. She sees these tools as helpful for students’ mathematics learning experience and her future teaching experience.

The IST Face - The CIST Didactic Tetrahedron

The instructor, students, and DT (IST) face considers students using DT as tools for communicating with their instructor regarding course content, thus, completing the CIST didactic tetrahedron. Students mentioned that DT was useful for online meetings or emailing instructors, as shown in Table 3.

Table 3. Participants Who Mentioned the IST Face

The IST Face	Participants
Online meetings	Alejandro, Sara
Emailing instructors	Said, Sara

For example, when we asked Sarah the question, "When you need help for the class, what do you typically do?" she mentioned:

> I'm not on campus a lot, so it's hard for me to go to things like office hours or tutoring centers. So, it's more of a, I'm doing it, like, you know, 10 o 'clock at night or something. So it's easier sometimes if I'll just Google part of it, or I'll just send an email to the instructor and table it for the day.

Sarah noted that emailing an instructor is convenient when not having other resources available outside regular business hours.

When we asked the same question about what they did when needing help in calculus class, Alejandro mentioned, "One-on-one teacher meetings are just better, just cause you don't have the pressure of the whole class listening to your questions." Alejandro used this context to explain the need for online office hours.

> Sometimes teachers' office hours are in the classroom only. And I think, um, maybe having one in the classroom and, like, one online where you could join like a, like a, Blackboard Collaborate. I think that would be good also just for, like people commute and stuff, like me 'cause I have a 40 minute commute. And if I don't, if it's some, if a teacher's office hours is one day that I don't have classes, I'm not going to drive 40 minutes to go to their office hours. You know, it's like a really big hassle and it's kind of a lot of money also on gas and the mileage on your car. So I think making office hours also available online at least once a week would be pretty beneficial.

Alejandro's comments highlight a critical gap in accessibility, especially for students with long commutes or financial constraints. By suggesting that instructors offer online office hours through platforms like Blackboard Collaborate, he emphasizes the importance of flexibility in supporting students who cannot attend in-person sessions. This situation points to a broader issue of equity in education, where logistical barriers like transportation and cost can disproportionately affect certain student groups.

The Sphere: Students Describe the Context While Using Technology

In addition to the faces of the CIST didactical tetrahedron, we found that students also described external factors already present in their calculus classes or ones they wished they had. The results of the sphere, which represents the context, include classroom environment, facilities, and accessibility. These results are shown in Table 4.

Table 4. Participants Who Mentioned the Sphere

The Sphere	Participants
Classroom environment	Alejandro, Bria, Diana, Georgia, José, Nathan, Said, Sarah
Facilities and accessibility	Alejandro, Bria, Diana, José, Nathan, Said, Sarah

Classroom Environment

Students discussed the classroom environment while using technology. Some students described how DT should be used in their calculus classes. For example, Nathan described a wish list for a calculus classroom with technology and active learning:

> I think they were called smart boards that we had in, I think it was, either at high school or middle school, and they were kind of experimenting with them at the time. But you could go up, and you could just, like, kind of draw on like the projector screen in a way. And it would take an input like that. But maybe something that's more laid flat out and everybody can kind of gather around and see that way.

Nathan's reflection on smart boards reveals both the potential and limitations of DT. While interactive tools like smart boards offer opportunities for engagement, the student's suggestion for a more accessible, flat interface indicates that current setups may not always promote inclusive, collaborative learning. This critique highlights the importance of designing classroom technologies prioritizing visibility and group interaction rather than just individual use to enhance collective learning experiences.

Facilities and Accessibility

Students discussed facilities and accessibility to DT. In this category, students described their access to the online textbook, the institutional facilities, and the access to several DT. For example, Bria explained there was no financial burden in buying all calculus textbooks because she "found them online free." However, when prompted, she revealed the source of these free textbooks, but it was not a legitimate distributor of the textbook used at the institution. Other "free textbook" practices were also found, such as taking pictures of the physical textbook to access the content. Diana described this practice, noting how if she "couldn't see the book online, [she] could ask someone to take pictures of their book and [she] could read it there with the pictures." These practices indicate that students may face financial challenges in purchasing course materials.

In several opportunities, Alejandro mentioned that using DT in calculus classes would be beneficial but may cause issues with access to the content if someone has internet or computer issues. Alejandro appreciated access to DT in this institution: "Now the access to the internet is pretty, pretty, pretty good, especially at [institution's name] with, like, computer labs and stuff." Alejandro also noted that there is an issue with awareness of resources as many students were not aware of them:

> I wasn't even aware of that. So maybe bring awareness to these types of resources also. Because I mean, I've been at [institution's name]. It's gonna be my third year and I had no clue about that. So maybe if, like, math teachers also bring awareness to these types of resources because all I hear about is the tutoring center.

Alejandro states that resources should be advertised better at the institution and possibly have as good of an advertisement system as the tutoring center.

Sarah, a commuter student, mentioned struggling to find the help she needed from the institution. She would like to have online tutoring support when needed.

> The only thing I could really think of in regards to calculus would be like, you know, having some kind of online tutoring option. I don't know if anything like that exists now. But just something like, because

> especially for me, the hours that I'm doing this, you know, can be really early in the morning or late at night if I'm doing the homework or review. And just having some other options to ask questions where you don't have to wait four hours for an answer that you can have a better response time.

Sarah's suggestion for online tutoring highlights the necessity for more immediate and flexible support systems in calculus education. Unconventional studying hours underscore the challenges that many students face in balancing coursework with personal or professional responsibilities, indicating that traditional office hours may not adequately meet their needs. Having this option would facilitate a more supportive learning environment.

Discussion

Students described the uses and benefits of generic and mathematics-specific DT apps and tools in calculus classes, highlighting how these benefits can enhance the teaching and learning of calculus. However, they also reported encountering several challenges. These challenges present an opportunity for researchers and instructors to critically reevaluate existing policies and practices to understand better and address the underlying reasons for these difficulties.

CST Interaction: Benefits and Challenges

Participants actively described the CST interaction between calculus content, students, and DT in various scenarios. These scenarios included reviewing concepts, visualizing and exploring calculus content, doing online homework, looking for similar examples, checking work, and speeding up the process. Using DT allowed students to look for similar examples, which were perceived as a benefit. This finding is aligned with what others have found in calculus classes, where students like to mimic completed examples (Dorko, 2021; Esparza Puga & Sánchez Aguilar, 2021). While using similar examples is perceived as beneficial, finding comparable solutions might take priority over engaging with the deeper underlying principles. Future research can examine the relationship between the use of similar examples and the learning of these concepts.

Our study adds to the literature on the exploration of students' perspectives about using three-dimensional DT, such as CalcPlot3D, for visualization and exploration of calculus concepts. Participants explained that three-dimensional mathematical software supports visualization and exploration of concepts. They also perceived them as tools for supporting their conceptual understanding of limit bounds in Calculus III. Limited research has examined the use of three-dimensional mathematics software programs to teach calculus (Martínez-Planell et al., 2023). Martínez-Planell et al. (2023) found that instructors liked CalcPlot3D for visualizing concepts and building conceptual understanding. This matches our findings from the students' point of view.

We found that DT can supplement students' learning experience by providing *more time and options,* as Sarah described. For example, students who cannot attend their classes supplement the instructor's notes or browse concepts online through videos. This is convenient and preferred as a first resource by many students because the resources are "right there for you" (Alejandro). While research has examined the importance of attendance for the academic performance of calculus classes (e.g., Khan, 2022), we did not find literature examining the use of DT as supplemental for providing broader access for students who were not attending classes. This can inform researchers of further problems to explore. Instructors may consider incorporating DT as supplemental tools to support students who can not attend classes due to personal challenges or larger responsibilities. While some students may miss class by choice, it is important to acknowledge that others face circumstances beyond their control. Providing these students with alternative resources could foster more equitable teaching practices in calculus, ensuring they still have access to learning opportunities.

Students perceived the use of online homework as a challenge. We found that students do not feel online learning feedback is meaningful for their learning experience. Researchers have examined online homework as a source of feedback and have found that students perceive it as accessible, adaptable, and useful for giving immediate feedback (Lampe & White, 2023). Similarly, Dorko (2020) has found that students used their online homework feedback to guide them in solving calculus problems. Meanwhile, Lampe and White (2023) indicated that calculus students reported that online homework did not allow them to keep track of their progress. Our study brings a new perspective to the existing literature, adding some considerations for the teaching and learning of calculus as students did not perceive online homework feedback was enough for their learning.

The concern about the lack of feedback in calculus classes may have implications for instructors and coordinators. This issue may serve as an opportunity to revise the online homework platforms used at the institution and the problems selected. The selection of other homework platforms or the careful choice of online homework problems may provide more detailed feedback for students that may support their learning. As we share these findings with the participants' institution, changes have been made in selecting homework problems. For example, homework problems now provide clickable support for students, such as directing them to content materials or instructional videos.

CIT Interaction: Benefits and Challenges

Participants described the CIT interaction between calculus content, instructor, and DT when discussing how instructors shared course materials using DT, selected online homework problems, and used DT to solve mathematical problems. Students discussed how instructors use *generic* DT tools for sharing course materials, such as posting notes and slides in the institutional learning management system. Generally, these were perceived as beneficial, which matches what other research has found (Loch, 2005; Maciejewski, 2016; Othman et al., 2017; Vajravelu & Muhs, 2016). However, our study brings insights into using generic DT apps and tools with caution as students perceived they faced challenges when instructors used DT, such as PowerPoint, to show already-solved examples. This finding suggests that students want to see step-by-step processes for solving calculus problems. This can inform instructors to cautiously use PowerPoint or other presentation software with blank spaces to work on the examples during class time instead of just showing solved examples.

Students highlighted additional challenges, including a lack of alignment between online homework and in-class examples and differences between the types of problems discussed in class and those in the online homework.

This misalignment, not previously addressed in the literature, suggests a need for instructors and course coordinators to ensure better consistency between homework assignments and classroom content. For instance, incorporating more word problems could help bridge this gap and enhance coherence in problem-solving approaches.

Our study adds to the limited research on students' perceptions of instructors' use of *mathematics* DT apps and tools. We found that students generally had positive experiences with these tools, particularly when instructors used platforms like Desmos, three-dimensional software, and Wolfram Alpha. Students appreciated how these tools helped them visualize concepts and solve problems, serving as effective models for independent work. Notably, many students reported that they began using dynamic software on their own after being introduced to it by their instructors. This was also found when examining future teachers' perceptions in a calculus class, who discuss how mathematics DT apps and tools used by their instructors, such as GeoGebra, provided visualization and conceptual understanding (Nongharnpituk et al., 2022). The use of mathematics DT apps and tools not only enhanced their in-class understanding but also provided valuable resources for tackling calculus problems independently. One implication of this finding is the power of instructors to present tools to students that can offer them more options for solving problems independently.

CIST Interaction: Benefits and Challenges

When analyzing the CIST interaction between calculus content, instructor, students, and DT, students provided insights on how DT supported their learning experiences when they needed help with calculus classes. They specifically mentioned email communication and online office hours. The preference for email communication and online office hours may reflect a mind shift after the pandemic virtual world (e.g., Griffiths, 2020; Hsu et al., 2022; Swanson et al., 2020). Swanson et al. (2020) investigated the communication preferences of college students and found that email was preferred for academic communication. Hsu et al. (2022) examined STEM students' attitudes toward in-person and online office hours during the COVID-19 pandemic, finding that many students perceived online office hours as convenient. Although these studies do not focus specifically on calculus courses, they provide insights into a potential tendency among STEM students to use email and online office hours more frequently.

Griffiths (2020) explored the perceptions of calculus students in Florida during the pandemic and observed that while most students wanted to return to in-person classes, a portion preferred to retain online office hours. Further research could delve into the specific reasons calculus students use online office hours and email instructors in order to develop coordinated policies that enhance inclusivity in calculus instruction.

The Context: Benefits and Challenges

Regarding the context, which we depicted as the *sphere*, we found that students discussed matters of access and technology. Consistent with Ní Shé (2023), participants mentioned having accessibility issues with the technology. Ní Shé's findings in mathematics courses about the students' challenges to access technology also hold for calculus courses. However, while considering the specific context of the participants' institution, students explained that while some students may not own the DT required for a class, the institution facilitated these resources.

Our findings reveal that while students did not explicitly refer to the cost of textbooks as a financial burden, some reported engaging in non-legal methods to access their course materials by using DT. This suggests that financial challenges may still be prevalent within the participants' institution, prompting students to find alternative and unauthorized solutions. These insights have already led to transformative changes in the institution's calculus courses, which are now using open educational resources. This study underscores the importance of understanding institutional contexts, and we encourage other researchers to conduct similar studies, considering their students' financial realities and exploring options such as low-cost materials and open educational resources.

Students emphasized the need for more active use of technology in calculus instruction, highlighting the importance of thoughtful lesson planning to achieve this. Young et al. (2018) recommend that instructors deliberately consider the role of technology when designing mathematics lessons, ensuring its integration is purposeful and aligned with learning objectives.

Implications and Limitations

We share position statements and recommendations from several national professional organizations about the effective use of technology in mathematics. The National Council of Teachers of Mathematics (2023) calls for planning with appropriate professional development to learn when, what, how, and why to integrate DT effectively. The insights provided by students in this work could inform professional development for instructors and training for students.

Our findings suggest a need for greater training for students on the use of technology (Ferrara et al., 2006). This aligns with the recommendations of the Mathematical Association of America (n.d.), stating that to enable our students to learn to use new DT, faculty, departments, and institutions must work together to ensure access to these resources. Other factors to consider for training and professional development are that faculty and institutions should consider the economic, ethical, pedagogical, mental, or physical barriers of DT on both faculty and students before implementing them, acknowledging their feedback, and evaluating the effects of the use of technology (American Mathematical Association of Two-Year Colleges, 2018).

We know that there are external factors and particular contexts that we may not control when implementing technology; however, it is remarkable that access to professional development opportunities is a key component for the effective use of DT in mathematics education. Accessibility is also a crucial factor for effective implementation. As mentioned earlier, these barriers occur in the classroom and extend to the institutional and household levels. Hence, a comprehensive analysis involving students, faculty, and institutional leaders is essential to develop strategies that positively impact the teaching and learning of mathematics, particularly in calculus classes.

We recognize some limitations of our study, including the small sample size and its exclusive focus on students' perspectives regarding DT use in several calculus sections within a single institution, each led by instructors with diverse teaching techniques and course policies. Nonetheless, our findings offer valuable insights to help instructors make informed decisions about the advantages and challenges of integrating DT into calculus instruction. We encourage future research to explore small, context-specific institutions to deepen understanding of these unique educational settings. Additionally, future studies should consider more coordinated course sections and incorporate instructors' perspectives on using DT in teaching and learning calculus for a more comprehensive analysis.

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Appendix. Interview and Demographic Survey Questions

Semi-structured interview questions:

1. Describe your experience using technology in calculus classes (if any).
2. Do you think using technology is beneficial for your learning experience? Why?
3. What kind of technology do you use in calculus classes?
4. What kind of technology would you like instructors to use in calculus classes?
5. When you need help for the class, what do you typically do?
6. How do you describe an ideal classroom to teach math?
7. Do you think that our classrooms are designed to use active learning practices?
8. Which assessments do you prefer for calculus classes?
9. How do you prepare for the class assessments?
10. Do you have any issues accessing the class materials?
11. Do you have any suggestions for faculty and staff to enhance your learning experience in calculus classes?
12. Is there anything else you want to share that I didn't ask?

Demographic information:

1. What is your current year in college? Freshman/Sophomore/Junior/Senior/Graduate Student/Other.
2. Which calculus course are you enrolled in this semester? Calculus I/ Calculus II/ Calculus III.
3. Are you a transfer student? Yes/No/Prefer not to respond.
4. Which department or college does your major belong to? College of Business/ College of Education/ College of Engineering/ College of Health and Human Sciences/ Department of Computer Science, Department of Biological Sciences, Department of Chemistry and Biochemistry, Department of Earth, Atmosphere, and Environment/ Department of Mathematical Sciences/ Department of Physics/ Department of Statistics/ Undecided/ Other.
5. Are you a transfer student? Yes/No/Prefer not to respond.
6. Which of the following describes your current situation? (Select all that apply)
    - I have a full-time job
    - I have a part-time job (less than 20 hours a week)
    - I am a parent
    - I have a long commute
    - I have transportation issues
    - I have financial struggles
    - I can't afford textbooks
    - None of the above