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Interactivity and accessibility in TPACK-integrated e-learning to enhance the quality of calculus learning

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Abstract

The quality of Calculus learning in higher education remains a challenge, as instructional practices tend to be predominantly procedure-oriented, thereby limiting opportunities for meaningful learning interactions and for concept visualization that supports conceptual understanding. This study aims to examine content validity and learning effectiveness in Calculus instruction through TPACK-integrated e-learning. The research employed a Research and Development (R&D) approach using the ADDIE model (Analyze, Design, Develop, Implement, and Evaluate. The developed instrument consisted of 20 items encompassing interactivity aspects across three dimensions and accessibility aspects based on four principles. Content validation was conducted by three experts using Aiken's V index. The results indicated that all instrument items were content-valid and were categorized as relevant to highly relevant. Furthermore, the effectiveness test results showed that the proportion of students achieving classical mastery exceeded the established threshold, and students' learning improvement fell into the high category. Additionally, the effect size analysis shows that implementing TPACK-integrated e-learning has a very strong impact on students' understanding. These findings confirm that TPACK-integrated e-learning is not only valid and effective but also has a substantial impact on enhancing the quality of Calculus learning in higher education.

Keywords:
Accessibility, Calculus learning quality, Interactivity, TPACK integration

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1. INTRODUCTION

The development of digital technology has brought about major changes in the world of education, particularly in the implementation of e-learning. This learning model enables the teaching and learning process to be more flexible, dynamic, and contextual, thereby addressing the challenges of education in the digital age (Hernandez-de-Menendez et al., 2020). However, the success of e-learning is not solely determined by the availability of content but also by how the learning system can accommodate active student engagement through interactivity and accessibility. According to Anderson (2008), successful e-learning is always characterised by high levels of interactivity, while Burgstahler (2020) argues that accessibility is an absolute requirement for digital media to be widely used. In line with the principles of multimedia learning, multimedia-based learning can strengthen the understanding of abstract concepts through a combination of text, visuals, and animation (Mayer, 2020; Moreno & Mayer, 2007).

Interactivity and accessibility are critical factors in supporting effective e-learning, particularly in Calculus instruction. Interactivity describes how students engage during the learning process (Moore, 1989). In the context of Calculus learning, learner–content interaction is manifested through concept exploration and contextual problem-solving activities that allow students to construct understanding independently and meaningfully (Clark & Mayer, 2023; Mayer, 2020). Learner–educator interaction occurs through instructors' feedback on students' solutions, conceptual discussions, and clarification of abstract concepts that frequently lead to misconceptions in Calculus learning (Hattie & Timperley, 2007). Meanwhile, learner–learner interaction is facilitated through group discussions and collaborative tasks that encourage students to communicate mathematical ideas, compare solution strategies, and construct knowledge socially (Johnson & Johnson, 2014; Slavin, 1995).

In addition to interactivity, the complexity of mathematical representations in Calculus often becomes a significant barrier for students when learning environments are not designed with adequate accessibility. The Web Content Accessibility Guidelines (WCAG), through the POUR framework, provide essential guidance for designing e-learning environments that support optimal accessibility (World Wide Web Consortium, 2023). The Perceivable principle is implemented by presenting learning materials through clear mathematical text, graphical visualizations, and audio explanations to ensure that information can be perceived by students with diverse characteristics (Burgstahler, 2020). The Operable principle ensures that navigation and learning activities can be accessed easily across various devices, while the Understandable principle emphasizes consistency in instructions and systematic presentation of problem-solving steps (Clark & Mayer, 2023). The Robust principle guarantees compatibility across platforms and assistive technologies, ensuring the sustainability of e-learning access over time (Kelly et al., 2004).

The quality of Calculus learning in higher education continues to face various challenges that reflect the overall low standard of instructional practice. Learning remains predominantly dominated by procedural and algorithmic approaches, leading students to focus more on symbolic manipulation rather than gaining a deep conceptual understanding. Moreover, students' active engagement in the learning process whether through discussion, exploration of concepts, or contextual problem-solving remains relatively low. Limited visualization of abstract concepts in Calculus also poses challenges that hinder students' conceptual comprehension. In the context of e-learning–based instruction, these problems are further amplified by insufficient interactivity between students and the content, lecturers, or peers, as well as accessibility issues that have yet to fully accommodate diverse learning needs. These conditions indicate the necessity of systematic efforts to improve the quality of Calculus learning by strengthening interactivity and accessibility within e-learning environments. In mathematics education at the university level, particularly in Calculus courses, the principles of interactivity and accessibility hold a high level of urgency. The abstract and symbolic nature of Calculus requires strong visualization and the support of easily accessible digital tools to enable students to comprehend relationships among concepts holistically (Tall, 1993). Calculus learning not only emphasizes procedural mastery but also deep conceptual understanding and mathematical reasoning (Orton, 1983). However, these challenges often arise due to the limitations of conventional learning media, which are unable to dynamically present three-dimensional visualizations, resulting in students struggling to connect mathematical symbols, graphical representations, and the geometric meaning of a concept (Stewart, 2016; Tall, 1993).

However, the reality in the field shows that the aspects of interactivity and accessibility in e-learning have not been fully achieved. Based on the results of a needs analysis conducted by the researchers using a questionnaire administered to students and lecturers, it was revealed that students still experience difficulties in understanding abstract Calculus concepts. These difficulties are characterized by the dominance of procedure-oriented learning, low levels of active student engagement, and limited opportunities for concept visualization. This aligns with Branch (2009) perspective, which emphasises that the development of instructional materials must be based on students' real needs to be truly relevant and effective. The lack of interactive features in teaching materials also contradicts Mayer (2020) multimedia learning theory, which emphasises the importance of multimedia representations such as combinations of text, visuals, and animations to support the understanding of abstract concepts. This condition indicates a gap between student needs and the learning strategies applied. Additionally, the results of the lecturer survey further reinforce the urgency of providing interactive and accessible learning media. As many as 75% of lecturers stated that the teaching materials currently used need to be improved in terms of interactivity and accessibility. E-learning will be more effective when it is designed by integrating interactivity and accessibility as the main elements (Bond, 2020; Martin et al., 2020). This condition indicates a gap in the use of technology to support pedagogical strategies that are aligned with the characteristics of Calculus material and students' learning needs, thus requiring an instrument that is content-valid and appropriate to the characteristics of e-learning.

In addressing these needs, the Technological Pedagogical Content Knowledge (TPACK) framework is seen as an appropriate solution. TPACK emphasises the alignment between content, pedagogy, and technology, enabling more meaningful learning (Chai et al., 2020; Mishra & Koehler, 2006). The integration of TPACK in e-learning does not merely serve as a medium for information transfer but also as a tool for interactive, collaborative, and accessible learning (Çam & Koç, 2024; Schmid et al., 2021). The selection of TPACK as a conceptual framework is based on its ability to address the limitations of conventional learning, which tends to separate technology, pedagogy, and content. By integrating all three in a balanced manner, TPACK is believed to be able to address the challenges of interactivity and accessibility in e-learning, while also promoting the creation of learning that is more inclusive, innovative, and oriented towards the development of 21st-century skills (Chai et al., 2019; Phillips, 2023). Based on this gap, the research question is: "Is the interactivity and accessibility instrument in TPACK-integrated e-learning valid and effective for evaluating Calculus learning?" In line with this question, this study aims to develop and validate an instrument for assessing the quality of interactivity and accessibility in Advanced Calculus learning delivered through TPACK-integrated e-learning, and to examine its effectiveness in enhancing students' learning outcomes.

2. METHOD

2.1. Study Design

This study employs the Research and Development (R&D) method with the primary objective of developing and testing the validity of integrated TPACK e-learning, focusing on interactivity and accessibility aspects. The development model used follows the ADDIE (Analyze, Design, Develop, Implement, Evaluate) steps, modified to suit the research context. The R&D approach was chosen because it can produce valid, practical, and effective learning products (Branch, 2009). The focus of this research is on the validation stage as an important process to assess the extent to which e-learning meets quality standards, particularly in terms of interactivity and accessibility. The research subjects consisted of expert validators. The validators involved learning technology experts. Their involvement aimed to ensure interactivity and accessibility in e-learning (Sugiyono, 2017).

E-learning for Advanced Calculus is implemented on the topic "Derivatives of Functions of Two Variables," as this topic represents a high level of difficulty in advanced mathematics learning. Through visual features, students can observe changes in function values with respect to two variables interactively, thereby facilitating the understanding of the concept of partial derivatives. The procedure for developing the interactivity and accessibility instruments in e-learning based on the ADDIE model can be seen in Figure 1.

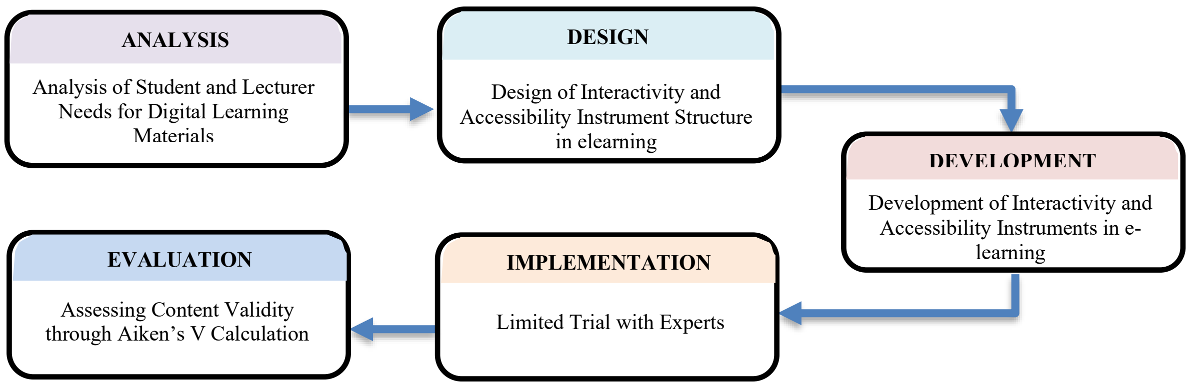

Figure 1. Procedure for developing the interactivity and accessibility instruments in e-learning

2.2. Instrument and Data Analysis

The validation process was conducted by providing the prototype of the interactivity and accessibility instrument along with validation sheets to three experts, consisting of one expert in mathematics education, one expert in educational evaluation, and one expert in educational technology. Each expert held a minimum doctoral qualification (PhD). The experts were asked to assign scores and provide comments on each item of the instrument (see

Table 1). The research instrument consisted of 20 items divided into two main constructs: interactivity and accessibility. The interactivity construct comprised 10 items, structured according to Moore (1989) framework, which distinguishes three dimensions of interaction: learner–content, learner–educator, and learner–learner. The accessibility construct consisted of 10 items, developed based on the Web Content Accessibility Guidelines (WCAG) framework, which operationalizes accessibility into four principles: Perceivable, Operable, Understandable, and Robust (World Wide Web Consortium, 2023).

Table 1. Operationalization of expert validation instrument for interactivity and accessibility

Aspect	Dimension/Indicator	Number of Items
Interactivity	Learner Content	4
	Learner Educator	3
	Learner Learner	3
Accessibility	Perceivable	3
	Operable	2
	Understandable	3
	Robust	2
Total		**20**

A Likert scale of 1–5 was used for validation, where 1 indicated "highly irrelevant" and 5 indicated "highly relevant." The experts' ratings were analyzed using Aiken's V index, calculated by the formula:

$$V = \sum \frac{S}{[n(c-1)]}$$

Where V = Aiken's index, S = $r - l_0$, r = rating score, l_0 = lowest score (1), c = highest score (5), and n = number of raters. The resulting Aiken's V values indicated the level of content validity for each item. For interpretation, Retnawati's (2016) classification was applied: 0.80 – 1.00 = "highly relevant," 0.61 – 0.80 = "relevant," 0.41 – 0.60 = "fairly relevant," 0.21 – 0.40 = "less relevant," and 0.00 – 0.20 = "not relevant." An instrument was considered to possess adequate validity if its average score reached the "relevant" category or higher (Aiken's V $\geq$ 0.61). In addition to quantitative analysis, this study also involved qualitative analysis derived from written comments and suggestions provided by experts through the validation sheets. The qualitative data were analyzed descriptively by categorizing expert feedback based on the clarity of indicators, the alignment of items with the constructs of interactivity and accessibility, and their relevance to the context of Calculus learning.

Furthermore, the effectiveness of the learning process was examined using an essay test administered to students after they participated in Calculus learning through TPACK-integrated e-learning. The effectiveness analysis was conducted using two statistical approaches: (1) a Binomial Test, used to assess classical mastery based on the percentage of students who achieved the minimum mastery criteria; and (2) a paired sample test, employed to determine the significance of differences between students' pretest and posttest scores following the learning intervention. To complement the paired-sample test analysis, an effect size analysis using Cohen's d was conducted to determine the magnitude of the impact of

TPACK-integrated e-learning on students' understanding. The resulting effect size values were then categorized according to Cohen's (2013) criteria (see Table 2).

Table 2. Effect size categories of Cohen's d

d Value	Effect Size Category
$0{,}00 \leq d < 0{,}20$	Very small
$0{,}20 \leq d < 0{,}50$	Small
$0{,}50 \leq d < 0{,}80$	Medium
$0{,}80 \leq d < 1{,}00$	Large
$d \geq 1{,}00$	Very large

The use of TPACK-integrated e-learning is considered to have an effect if the effect size value is at least in the medium category ($d \geq 0.50$).

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Analysis

The analysis stage is the initial step in the process of developing interactivity and accessibility instruments in TPACK integrated e-learning, which aims to identify the needs of students and lecturers in Calculus learning as the primary users of the learning process. The results of the needs analysis indicate that students still experience difficulties in understanding abstract Calculus concepts. These difficulties are caused by low levels of learning interactivity and limited accessibility of instructional materials. The learning process tends to be passive, characterized by minimal use of dynamic visualizations and limited opportunities for students to actively interact with the learning materials, lecturers, and fellow students. This condition has the potential to hinder students' conceptual understanding, as insufficient integration of interactivity and accessibility in e-learning environments can impede the process of meaning-making related to abstract concepts in mathematics learning.

From the lecturers' perspective, the questionnaire results indicate that the instructional materials currently used have not fully supported interactive and accessible learning, particularly in facilitating the representation of abstract concepts and the pedagogical use of technology. These limitations are primarily evident in the suboptimal facilitation of visual representations of Calculus concepts and the insufficient pedagogical use of technology to promote student engagement. Lecturers also require instruments capable of providing an objective picture of the quality of interactivity and accessibility of the e-learning being used. Therefore, the findings of this needs analysis serve as the basis for designing interactivity and accessibility instruments for TPACK-integrated e-learning that are aligned with the characteristics of Calculus learning and students' learning needs. In the digital era, calculus learning demands instructional materials that can visualize abstract concepts, facilitate independent learning, and enable online collaboration (Stewart, 2016; Tall, 1993). This stage provides the conceptual foundation that e-learning development must integrate mathematical content, pedagogical strategies, and technology (Koehler et al., 2017; Mishra & Koehler, 2006). Based on the needs analysis, interactivity and accessibility instruments within TPACK-integrated e-learning are required as an effort to enhance the quality of Calculus learning. These instruments are designed to measure and ensure the integration of content, pedagogy, and technology in digital learning, so that the learning process not only focuses on content delivery but also promotes active student engagement and ease of access to learning.

3.1.2. Design

Based on the needs analysis, the Design stage focuses on developing the instruments and e-learning system design for Calculus, emphasizing the integration of content, pedagogy, and technology in accordance with the TPACK framework. The instrument design includes two main aspects: interactivity and accessibility (see Figure 2). The interactivity aspect is adapted from Moore (1989) framework, which consists of three dimensions learner–content, learner–educator, and learner–learner. Meanwhile, the accessibility aspect is designed with reference to the POUR principles (perceivable, operable, understandable, robust) as stipulated in the Web Content Accessibility Guidelines (World Wide Web Consortium, 2023). The e-learning system for Calculus is developed with an interactive and visual learning structure, enabling students to explore calculus concepts through digital-based learning experiences. The learning content features audiovisual materials and digital collaboration spaces to support interaction among students and between students and instructors.

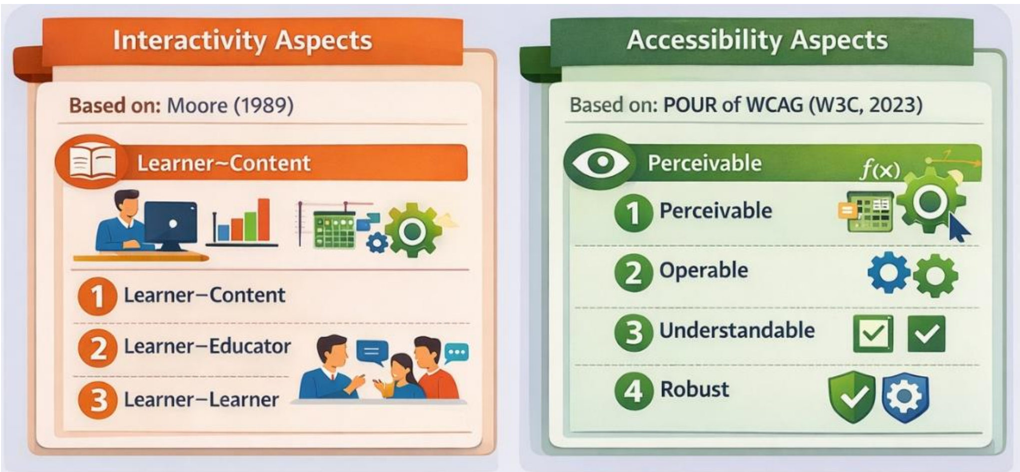

Figure 2. Design of interactivity and accessibility in TPACK-integrated e-learning

As an implementation of the conceptual design, the e-learning design was then realized through the arrangement of the user interface layout and system navigation, which were developed to be intuitive, responsive, and oriented toward ease of user access. The main e-learning menu interface is designed to be intuitive and responsive, displaying the course identity, learning topics, and main navigation tools to facilitate student access to all learning components. Each menu such as Dashboard, My Courses, and Site Administration provides quick access to learning materials, discussion forums, learning activities, and assessments available within the system. The main page interface of the TPACK-Integrated Calculus E-Learning can be seen in Figure 3.

Figure 3. Main page interface of the TPACK-integrated advanced calculus e-learning

This form of interactivity and accessibilty is reflected in the interface of the developed TPACK-Integrated Calculus e-learning system, as shown in Figure 4.

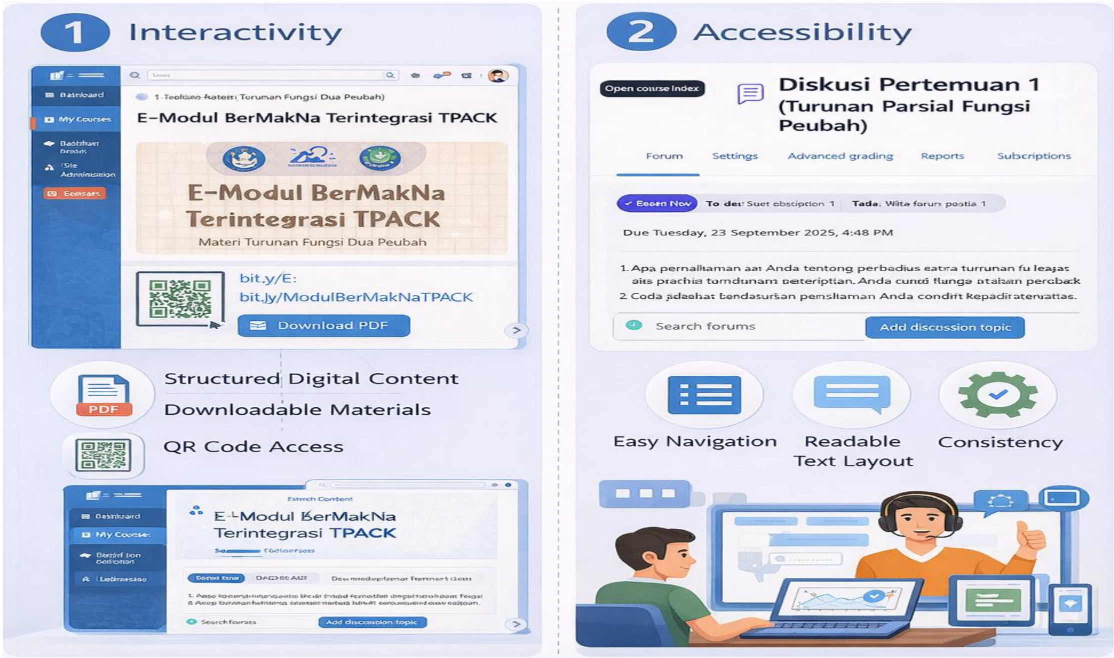

Figure 4. Interactivity and accessibilty of TPACK-integrated advanced calculus e-learning

3.1.3. Development

The experts assessed that the interactivity and accessibility instrument in TPACK-integrated e-learning developed in this study comprises two main aspects, namely interactivity and accessibility, which are formulated into 20 statements designed to represent the quality of e-learning in supporting Calculus learning. The interactivity aspect consists of three dimensions, namely learner–content, learner–educator, and learner–learner (Moore, 1989).

The learner–content dimension includes four statements representing the extent to which e-learning supports students' independent exploration through visualization, simulation, evaluation, and contextual problems. The learner–educator dimension includes three statements that assess the quality of pedagogical interaction between students and lecturers, particularly through feedback, conceptual discussions, and concept clarification. Meanwhile, the learner–learner dimension includes three statements that measure the extent to which e-learning supports collaborative learning through discussions and group tasks.

The accessibility aspect was structured based on the WCAG principles, which consist of four dimensions, namely Perceivable, Operable, Understandable, and Robust (World Wide Web Consortium, 2023). The Perceivable dimension includes three statements that assess the clarity of material presentation, visual representation, and the availability of supporting explanations. The Operable dimension includes two statements that assess the ease of navigation and the usability of e-learning across various devices. The Understandable dimension includes three statements that assess the clarity of instructions, consistency in material presentation, and the systematic nature of problem-solving steps. Meanwhile, the Robust dimension consists of two statements that assess the compatibility of e-learning with various devices and supporting technologies.

3.1.4. Implementation

At the implementation stage, a limited trial was conducted on the interactivity and accessibility instruments within the TPACK-integrated e-learning through expert judgment. This trial aimed to assess the content validity of each item of the developed instruments. The validation process involved providing the e-learning prototype along with validation sheets to three experts: one mathematics education expert, one educational evaluation expert, and one learning technology expert. The experts were asked to provide quantitative assessments in the form of scores for each statement item, as well as qualitative feedback in the form of comments, suggestions, and revision notes, which served as the basis for refining the instruments before their use in the subsequent stage. After the expert validation was completed, the next stage involved testing the effectiveness of the instrument and the learning process. The effectiveness test was conducted using essay type questions administered to students after they participated in Calculus learning through TPACK-integrated e-learning.

3.1.5. Evaluation

The validation results showed that TPACK integrated e-learning met the validity criteria in all aspects, so it was declared suitable for use in the learning process. Data analysis was conducted by combining quantitative descriptive analysis (based on average validation scores) and qualitative descriptive analysis (based on expert feedback and improvement suggestions). From the analysis results, several key points of concern were identified by the experts, including:

Instrument Testing Results

Before being implemented in the main study, the questionnaire instrument was first tested for content validity by involving a panel of experts. This process aimed to ensure that each item accurately measured the intended construct, demonstrated internal consistency, and aligned with the theoretical framework. Content validity analysis employed Aiken's V index, with a minimum coefficient threshold of 0.61 serving as the criterion for validity (Aiken, 1985). The developed instrument consisted of 20 items representing seven main aspects related to interactivity and accessibility in TPACK-based e-learning for calculus instruction.

Table 3. Content validity test results

Assessment Aspect	Item Code	Expert Ratings			Aiken's V	Category
		V1	V2	V3		
Learner Content	LC 1	5	5	5	1.00	Highly Relevant
	LC 2	4	4	4	0.75	Relevant
	LC 3	4	5	4	0.83	Highly Relevant
	LC 4	5	4	5	0.92	Highly Relevant
Learner Educator	LE 1	5	4	4	0.83	Highly Relevant
	LE 2	4	4	4	0.75	Relevant
	LE 3	5	5	4	0.92	Highly Relevant
Learner Learner	LL 1	4	4	4	0.75	Relevant
	LL 2	4	4	4	0.75	Relevant
	LL 3	4	5	4	0.83	Highly Relevant
Perceivable	PER 1	4	4	4	0.75	Relevant
	PER 2	4	3	4	0.67	Relevant
	PER 3	4	4	4	0.75	Relevant
Operable	OP 1	4	4	4	0.75	Relevant
	O2 2	4	4	4	0.75	Relevant
Understandable	UN 1	5	4	4	0.83	Highly Relevant
	UN 2	4	4	4	0.75	Relevant
	UN 3	4	4	5	0.83	Highly Relevant
Robust	RO 1	4	5	4	0.83	Highly Relevant
	RO 2	4	4	4	0.75	Relevant
	Average				0.80	Relevant

As presented in Table 3, based on the Aiken's V analysis, all items obtained values ≥ 0.61 and were therefore categorized as valid. Out of the 20 items, 9 were rated as highly relevant (Aiken's $V \geq 0.80$), while 11 were rated as relevant ($0.61 \leq V < 0.80$). The overall mean validity index was 0.80, indicating that the instrument fell into the "relevant" category and was feasible for use in the main study.

Interactivity

The evaluation of interactivity was conducted by adapting Moore's (1989) framework, which comprises three main indicators: learner–content, learner–educator, and learner–learner. Aiken's V index was employed to validate each indicator through expert judgment.

Table 4. Validation results of e-learning interactivity integrated with TPACK

Assessment Aspect	Aiken's V	Category
Learner–Content	0.88	Highly Relevant
Learner–Educator	0.83	Highly Relevant
Learner–Learner	0.78	Relevant

For the learner–content aspect, the validation results revealed four indicators that obtained an Aiken's V value of 0.88, categorized as highly relevant (see Table 4). Experts emphasized the importance of providing students with learning experiences that enable deeper exploration of materials through multimedia representations such as context-based simulations, visual animations, explanatory videos, and case-based exercises. The integration of TPACK in this context is reflected in the combination of content knowledge (CK) involving mastery of calculus concepts, technological knowledge (TK) through the use of interactive digital media, and pedagogical knowledge (PK) through the implementation of multimedia-based learning strategies. The principles of multimedia learning (Mayer, 2020; Moreno & Mayer, 2007) affirm that the use of multimedia representations strengthens understanding of abstract concepts while reducing cognitive load.

For the learner–educator aspect, the validation results indicated three indicators with an Aiken's V value of 0.83, categorized as highly relevant (see Table 4). This result underscores that interactivity between students and educators has been well accommodated in the TPACK-integrated e-learning design. Experts highlighted that interactive communication features greatly assist students in obtaining content clarification, academic guidance, and constructive feedback. This aligns with Vygotsky (1978) social constructivism theory, which stresses the importance of interaction with educators in building the zone of proximal development.

For the learner–learner aspect, the validation results revealed three indicators with an Aiken's V value of 0.78, categorized as relevant (see Table 4). Although not reaching the highly relevant category, experts acknowledged that peer collaboration features were adequate but required refinement. Suggested improvements included clarifying group communication flow, adding interactive document-sharing features, and providing more structured collaborative work guidelines. The importance of learner–learner interaction aligns with Johnson and Johnson (2014) theory of collaborative learning, which argues that group interaction fosters social skills, problem-solving abilities, and conceptual understanding. Within the TPACK framework, this aspect reflects a blend of pedagogical knowledge (PK) through collaborative learning strategies, technological knowledge (TK) through the use of online forums and learning management system (LMS) discussion features, and content knowledge (CK) to ensure that student interaction remains focused on calculus comprehension. Further research has shown that peer interaction in online learning environments can build socially shared regulation of learning, positively impacting conceptual understanding (Järvelä et al., 2016; Zhou & Tsai, 2023).

Overall, the validation results indicate that the interactivity aspect of TPACK integrated e-learning falls within the relevant to highly relevant category across all three indicators. These findings indicate that the e-learning design has been effective in facilitating content understanding through student content interaction and in providing pedagogical feedback. TPACK integrated e-learning tends to be stronger in supporting conceptual understanding and the provision of pedagogical feedback through interaction (Chai et al., 2020; Schmid et al., 2020). On the other hand, the relatively lower achievement on the learner–learner indicator suggests that collaborative features in e-learning have not yet been fully optimized to support social interaction and collaboration among students. Students interaction and collaboration are often the weakest aspects of e-learning when they are not designed through structured collaborative activities (Borba et al., 2016; Martin & Bolliger, 2018).

Accessibility

The evaluation of accessibility was carried out based on the POUR framework (Perceivable, Operable, Understandable, Robust) developed by World Wide Web Consortium (2023). Overall, the validation results indicate that the accessibility of TPACK-integrated e-learning falls within the “relevant” category. This finding suggests that the e-learning design sufficiently meets accessibility principles, though improvements are still required across all four aspects.

Table 5. Validation results of e-learning accessibility integrated with TPACK

Assessment Aspect	Aiken’s V	Category
Perceivable	0.72	Relevant
Operable	0.75	Relevant
Understandable	0.81	Relevant
Robust	0.79	Relevant

¬For the Perceivable aspect, the validation results yielded an Aiken’s V value of 0.72, categorized as relevant (see Table 5). Experts highlighted the need for improvements in several indicators: (1) instructional videos should include subtitles to support comprehension, (2) text must be presented with appropriate font size and color contrast to ensure readability, and (3) content should be delivered using clear and simple language. The integration of TPACK in this context is reflected in technological knowledge (TK) through the use of optimal visual design and multimedia, content knowledge (CK) in presenting materials using symbols, graphics, and narration, and pedagogical knowledge (PK) in employing user-friendly content strategies. Mayer (2020) multimedia learning principle supports the use of multiple representations to reduce cognitive overload and enhance understanding of abstract concepts.

For the Operable aspect, the validation results yielded an Aiken’s V value of 0.75, categorized as relevant (see Table 5). Experts recommended improvements to ensure: (1) e-learning is accessible across devices including computers, tablets, and smartphones, and (2) the system provides quick responses to user interactions. The integration of TPACK in this aspect is reflected in technological knowledge (TK) through mobile-friendly and responsive interface design, pedagogical knowledge (PK) in ensuring structured and consistent learning navigation, and content knowledge (CK) in maintaining easy-to-follow organization of calculus materials. Studies confirm that intuitive and consistent navigation enhances the effectiveness of user interaction with e-learning systems (Kelly et al., 2004; Liu & Correia, 2021).

For the Understandable aspect, the validation results yielded an Aiken’s V value of 0.81, categorized as relevant (see Table 5). Experts emphasized the importance of three indicators: (1) logically structured content that allows students to follow the learning flow easily, (2) clear instructions for completing activities, and (3) consistent presentation of information across sections. The integration of TPACK is demonstrated through pedagogical knowledge (PK) in systematic instructional strategies, content knowledge (CK) in providing well-structured and coherent calculus materials, and technological knowledge (TK) in the use of simple, consistent icons, activity symbols, and graphical elements in the user interface. The addition of visual icons was strongly recommended to reduce reliance on lengthy text instructions. This is in line with cognitive load theory (Paas et al., 2003; Sweller, 2020), which argues that visual representations reduce cognitive burden and accelerate comprehension.

For the Robust aspect, the validation results yielded an Aiken's V value of 0.79, categorized as relevant (see Table 5). Experts stressed the importance of ensuring: (1) e-learning can be accessed consistently across different devices without technical errors, and (2) compatibility with multiple platforms and operating systems. Experts also noted the limitations of PDF format in supporting interactivity and cross-platform flexibility, recommending the adoption of interactive web-based HTML5 instead. Within the TPACK framework, technological knowledge (TK) is represented through the use of HTML5, which enables multimedia integration, dynamic navigation, and cross-device compatibility; pedagogical knowledge (PK) through the alignment of instructional design with learning objectives; and content knowledge (CK) through the consistency of calculus materials across platforms. Robust digital design ensures long-term accessibility (Burgstahler, 2020; Seale, 2013).

In conclusion, the validation results across all four POUR aspects placed accessibility in the relevant category. This finding demonstrates that the TPACK-integrated e-learning design has achieved the minimum standard of accessibility. Adequate accessibility is an essential prerequisite for realizing inclusive and equitable digital learning, ensuring that all students have equal opportunities to access and utilize learning resources (Al-Azawei et al., 2016; Seale, 2013). However, further improvements are recommended in all aspects to ensure that the learning experience becomes more inclusive, adaptive, and sustainable. This is in line with the principle of TPACK integration, in which the use of technology functions not only as a medium for content delivery but also as a means to enhance access, student engagement, and the provision of more responsive and user-friendly learning navigation (Chai et al., 2020; Schmid et al., 2021).

To support validity, an effectiveness test was conducted involving 16 students solving Calculus problems. The effectiveness test consisted of a hypothesis test of classical mastery analyzed using the Binomial Test, as well as a hypothesis test of students' improvement conducted using a one-sample t-test, and an effect size analysis using Cohen's d to assess the magnitude of the learning effect.

Table 6. Results of classical mastery hypothesis testing using the binomial test

		Category	**N**	**Observed Prop.**	**Test Prop.**	**Exact Sig. (2-tailed)**
TEST	Not Mastery	<= 79.9	3	0.19	0.50	0.021
	Mastery	> 79.9	13	0.81		
	Total		16	1.00		

The decision rule for the Binomial Test is as follows: if the Sig. (2-tailed) value is less than 0.05, then H_0 is rejected; conversely, if the Sig. (2-tailed) value is greater than or equal to 0.05, then H_0 is accepted. Based on the test results presented in Table 6, the Sig. (2-tailed) value was 0.021, which is less than 0.05. Therefore, H_0 is rejected, indicating that the percentage of students achieving classical mastery exceeds 79.9%. Furthermore, to measure the magnitude of improvement in students' abilities, a paired samples testwas conducted on the N-gain values obtained from comparisons between pretest and posttest scores.

Table 7. Paired samples test analysis

	t	Df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
GAIN	22.913	16	0.001	0.77125	0.7036	0.8389

Based on the results presented in Table 7, the Sig. (2-tailed) value was 0.001, which is less than 0.05. Therefore, H_0 is rejected, indicating a significant increase in the mean normalized gain score of students' abilities, namely ≥ 0.30. According to Hake (1998), an average N-gain value in the medium to high category is generally interpreted as evidence of an improvement in students' abilities within the context of TPACK-integrated e-learning.

To determine the magnitude of the effect (effect strength) of implementing TPACK-integrated e-learning on improving the quality of Calculus learning, an effect size analysis using Cohen's d was conducted.

Table 8. Paired samples effect sizes

		Standardizer[a]	Point Estimate	95% Confidence Interval	
				Lower	Upper
Gain	Cohen's d	0.12696	6.075	3.865	8.274

a. The denominator used in estimating the effect sizes. Cohen's d uses the sample standard deviation.

Based on the effect size analysis of the gain scores in Table 8, a Cohen's d value of 6.075 was obtained, with a 95% confidence interval ranging from 3.865 to 8.274. Referring to the effect size categories, where $d \geq 1.00$ is classified as very large, these results indicate that the implementation of TPACK-integrated e-learning has a very strong effect on improving the quality of Calculus learning, particularly students' conceptual understanding.

3.2. Discussion

The interrelation between interactivity and accessibility in TPACK integrated e-learning serves as a fundamental factor in creating effective and meaningful digital learning experiences. Interactivity encourages students to actively participate through multimedia exploration, communication with instructors, and peer collaboration. However, the effectiveness of interactivity is highly influenced by the level of accessibility within the e-learning system, which ensures that all features can be used without technical barriers. The POUR principles of the Web Content Accessibility Guidelines (World Wide Web Consortium, 2023) guarantee that learning media are perceivable, operable, understandable, and robust across various devices. The validation results show that all aspects of interactivity and accessibility fall within the relevant to highly relevant category, indicating that this e-learning meets pedagogical and technological standards to support inclusive learning experiences. The operational integration of TPACK is able to enhance the quality of digital learning design, particularly through alignment between the technology used, pedagogical strategies, and the characteristics of instructional content (Chai et al., 2020; Schmid et al., 2021).

These findings are further reinforced by the results of the validation of the instrument used to assess the quality of interactivity and accessibility in TPACK integrated e-learning. The clarity of item wording, the alignment of indicators with measurement objectives, and the consistency between operational definitions and instrument statements reflect the fulfillment of content validity principles (Haynes et al., 1995; Retnawati, 2016). The integration of the TPACK framework within this instrument ensures that technological, pedagogical, and content aspects are not treated separately, but instead mutually reinforce one another in supporting Calculus learning that requires conceptual visualization, continuous pedagogical feedback, and flexibility of access across devices. Mayer (2020), and Hattie and Timperley (2007) emphasize that technology based visualization and feedback play an important role in enhancing students' conceptual understanding. Nevertheless, the analysis results indicate that the level of interactivity achievement has not been fully balanced by the optimization of accessibility aspects across several indicators, underscoring that the effectiveness of interactivity is highly dependent on the level of accessibility in e-learning. Interactivity and accessibility are two interdependent and inseparable aspects in the development of TPACK integrated e-learning, as limitations in accessibility can hinder the utilization of interactive features (Al-Azawei et al., 2016; Burgstahler, 2020; Seale, 2013).

TPACK integrated e-learning needs to be developed by positioning interactivity and accessibility as two complementary aspects. Interactivity designed through the use of multimedia, formative feedback, and collaborative activities must be easily and consistently accessible across various devices and platforms (Al-Azawei et al., 2016; Seale, 2013). The TPACK framework provides a clear operational foundation for integrating Technological Knowledge, Pedagogical Knowledge, and Content Knowledge in a balanced manner within e-learning design (Chai et al., 2020; Schmid et al., 2021). Digital accessibility principles emphasize that learning quality is not determined solely by the sophistication of the technology used, but also by the system's ability to ensure equitable learning engagement for all students (Burgstahler, 2020; World Wide Web Consortium, 2023). In the context of Calculus learning, the balance between interactivity and accessibility becomes increasingly important, as conceptual understanding relies heavily on dynamic visualization and sustained cognitive engagement. The integration of TPACK can help students understand the relationship between mathematical symbols, graphs, and geometric meaning. An intuitive and mobile-friendly interface design facilitates both independent and collaborative learning, in line with the principles of Universal Design for Learning. The balance between interactivity and accessibility positions e-learning not merely as a medium for delivering content, but as an active learning environment capable of enhancing learning quality (Fiorella & Mayer, 2015; Tall, 1993). Therefore, TPACK-integrated e-learning needs to be continuously developed by positioning interactivity and accessibility as complementary aspects.

Interactivity and accessibility in TPACK-integrated e-learning make a significant contribution to improving the quality of Calculus learning. The findings show that the implementation of TPACK-integrated e-learning not only meets validity criteria but also demonstrates a high level of effectiveness in supporting students' learning quality. Statistical analysis of learning mastery indicates that the proportion of students who achieved mastery exceeded the established criteria, confirming that the learning process was effective. According to Field (2024) and Sugiyono (2017), the Binomial Test is appropriate for determining whether a sample proportion differs significantly from a specified criterion value, particularly in the context of assessing learning mastery in experimental research.

Furthermore, the results of the learning gains analysis indicate an improvement in students' understanding after participating in TPACK-integrated e-learning. This is consistent with Ausubel's (2000) emphasis on the importance of interactivity, visualization, and active cognitive engagement in fostering meaningful conceptual understanding. The high N-gain value reflects that the learning process not only improved learning outcomes quantitatively but also effectively facilitated deeper conceptual understanding of Calculus (Hamid et al., 2025; Schmid et al., 2020). To strengthen the interpretation of the statistical test results, an effect size analysis was conducted. The results show that the learning intervention produced a very large effect, indicating that the improvement in students' understanding was not only statistically significant but also represented a strong and meaningful contribution to the learning process (Cohen, 2013). These findings confirm that TPACK-integrated e-learning is an effective instructional approach and makes a substantial contribution to enhancing students' understanding and the overall quality of Calculus learning in higher education.

4. CONCLUSION

This study resulted in the development of an evaluation instrument for interactivity and accessibility in TPACK integrated e-learning that has been proven to possess content validity and is appropriate for use in Calculus learning in higher education. All instrument items were rated as relevant to highly relevant by experts, indicating that the instrument functions as a valid measurement tool for assessing the quality of TPACK integrated e-learning, particularly in terms of interactivity and accessibility. The developed instrument is able to comprehensively represent the dimensions of interactivity (learner–content, learner–educator, and learner–learner) as well as the POUR accessibility principles (Perceivable, Operable, Understandable, and Robust). The implementation results indicate that the application of TPACK-integrated e-learning has a positive impact on the quality of Calculus learning. The learning process not only supports students in achieving learning mastery but also significantly enhances their conceptual understanding. Furthermore, the analysis shows that the learning effect falls within the very large category, confirming that TPACK-integrated e-learning exerts a strong influence on Calculus instruction. Overall, the main contribution of this study lies in two key aspects: the development of a valid TPACK-integrated e-learning evaluation instrument and the provision of empirical evidence on the magnitude of the learning effect generated by the implementation of TPACK-integrated e-learning on students' abilities. The instrument developed is expected to serve as a reference for lecturers and researchers in evaluating learning quality, while also strengthening the position of TPACK-integrated e-learning as an effective and highly impactful instructional approach for Calculus learning in higher education.

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Declarations

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