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Investigating the limit of peer collaboration: Insight from worked-example in multivariable calculus

Cecep Anwar Hadi Firdos Santosa[1*], Mehmet Filiz[2]
[1]Department of Mathematics Education, Universitas Sultan Ageng Tirtayasa, Banten, Indonesia
[2]Department of Educational Sciences, Amasya University, Amasya, Turkey
[*]Correspondence: cecepanwar@untirta.ac.id

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Abstract

This study validates the superiority of individual learning over peer collaborative learning when studying worked examples in a multivariable calculus course. It examines cognitive load dimensions and the quality of students' conceptual understanding to provide empirical recommendations for instructional design in higher education. A mixed-method approach with a concurrent triangulation design combined quantitative and qualitative analyses. The quantitative aspect involved experimental comparisons of cognitive load, comprehension tests, and surveys, while the qualitative analysis focused on interaction patterns through discussion transcripts. Participants included 131 undergraduate students (41 male, 90 female, average age 19.25 years) from a state university in Banten, Indonesia. They were randomly assigned to individual (52 students) and peer collaboration (79 students) groups. The results revealed that students in the individual learning condition achieved significantly better comprehension than those in peer collaboration, though cognitive load showed no difference between the groups. Peer collaboration presented notable challenges in supporting the effectiveness of worked-example learning. In most cases, collaboration was either ineffective or partially effective. However, instances of effortful understanding and clarification-seeking suggest collaboration may be supportive if instructional design encourages deeper engagement and problem-solving. These findings provide insights for optimizing collaborative strategies in worked-example learning.

Keywords:
Cognitive load, Individual learning, Instructional design, Peer collaboration, Worked-example

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1. INTRODUCTION

Multivariable calculus is one of the courses offered in all mathematics education program. This course requires prerequisite knowledge, including differential and integral calculus. Moreover, multivariable calculus serves as a foundation for other advanced mathematics courses and even interdiciplinary subjects. This highlights the importance of mastering the course, as students who struggle with it are likely to face challenges in comprehending more advanced mathematical concepts and applications (Hashemi et al., 2015; Kashefi et al., 2012; Martínez-Planell & Trigueros, 2021; Wagner, 2018).

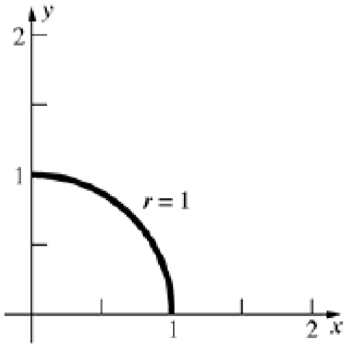
The fundamental difference between multivariable calculus and differential and integral calculus (commonly referred to as single-variable calculus) lies in the change of the function's domain, which shifts from a single variable ($f: \mathbb{R} \to \mathbb{R}$) to multiple variables ($f: \mathbb{R}^n \to \mathbb{R}$) (Jones & Dorko, 2015). While students are expected to have studied these prerequisites, in practice, they often encounter difficulties in mastering topics within multivariable calculus (Khemane et al., 2023). This course is frequently perceived as complex and challenging for students. This means that when they learn the content in this course, they can be considered as novice learners.

For example, when students are faced with the problem of proving the limit value of a two-variable function (formally using $\epsilon - \delta$) as follows: $\lim_{(x,y)\to(1,3)} (2x + 3y) = 11$. To prove this limit is correct, students must be able to extend the concept of distance in $\mathbb{R}$, to the concept of distance (norm) in $\mathbb{R}^2$. Additionally, students must be able to geometrically illustrate the function in $\mathbb{R}^3$. Another example is when students are asked to determine the limit value: $\lim_{(x,y)\to(0,0)} \frac{xy}{x^2+y^2}$. In their mental, the concept of limits they are familiar with involves left and right hand limits. However, these concepts cannot be applied to solve the limit of a two-variable function. Instead, understanding the concept of a limit around a point is required, the limit value at the point (0,0) must be approached from various directions. Similarly, an example arises when students solve problems involving double integrals. Khemane et al. (2023) highlight students' difficulties in swapping the order of integration. These examples demonstrate the complexity of solving multivariable calculus problems, where many mathematical concepts are involved, such as three-dimensional geometry, vectors, the use of geometric and graphical representations, and, of course, a deep understanding of functions.

Beyond the inherent difficulty of the material, other significant factors that are believed to influence students' understanding are related to didactic and pedagogical aspects. The didactic aspect concerns how concepts are presented to students, whereas the pedagogical aspect involves guiding students in terms of their social, emotional, moral, and intellectual development. In the information processing theory (a sub-theory of cognitivism paradigm), the failure of information to become knowledge occurs when the information processed in working memory cannot be stored in long-term memory (Sweller, 2022, 2024; Sweller et al., 2019). According to this learning theory, when learning something complex, working memory becomes overloaded with the abundance of new information being processed, leading to a condition known as cognitive overload. This condition arises because human working memory is highly limited (Baddeley, 2000, 2010, 2012, 2017, 2019; Baddeley & Larsen, 2007). Moreover, classic studies by Miller (1956) and Peterson and Peterson (1959) state that human working memory can only process approximately 7 ± 2 chunks of information and can retain them for only about 20 seconds.

In the learning process, one method proven to reduce cognitive load is the worked-example approach. The use of worked-examples has been extensively researched and demonstrated to reduce cognitive load (particularly extraneous cognitive load) experienced by students (Asmara et al., 2024; Booth et al., 2013; Chen et al., 2019; Hu et al., 2015; Kalyuga, 2011; Lee & Ayres, 2024; Renkl, 1997; Renkl & Atkinson, 2010; Rourke & Sweller, 2009; Sweller, 2011). Aligned with these studies, Santosa et al. (2018) conducted research to assist students in understanding the concepts and solving problems in multivariable calculus by modifying textbooks and presenting them in the form of worked-examples. These worked-examples were presented in a tabular format containing step-by-step problem-solving procedures accompanied by explanations for each step (Table 1 for example). Furthermore, the study measured students' cognitive efficiency, which links cognitive load to their knowledge acquisition.

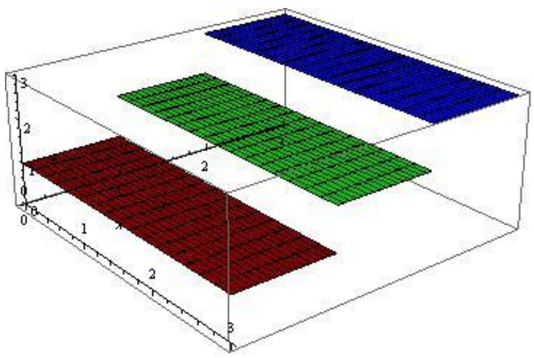
Table 1. Worked-example with explanation

No	Solution Steps	Explanation
1	$\int_0^1 \int_0^{\sqrt{1-x^2}} (4-x^2-y^2)^{-\frac{1}{2}}\, dydx$	Problem
2	 	This plot is obtained from the integration limit. The interval y is located from $y = 0$ to $y = \sqrt{1-x^2}$, so, $x^2 + y^2 = 1$ $\leftrightarrow y^2 = 1 - x^2$ $\leftrightarrow y = \sqrt{1-x^2}$ It is a semicircle above x-axis, with radius ($r = 1$). in polar coordinates, r is located from $r = 0$ to $r = 1$ The boundary of x, located from $x = 0$ to x =1, transforming to polar coordinat, $\theta = 0$ to $\theta = \frac{\pi}{2}$.
3	$\int_0^{\frac{\pi}{2}} \int_0^1 (4-r^2)^{-\frac{1}{2}} r\, dr\, d\theta$	Changing to polar coordinates, remember that: $x = r\cos\theta$, $y = r\sin\theta$, $x^2 + y^2 = r^2$, and $dydx$ changed to $r\ dr\ d\theta$ Notice the change in the integral boundary.

In students' cognition, worked-examples elicit the process of self-explanation, which is a mental process involved in solving a problem. Self-explanation functions as verbal/non-verbal mediation that supports the transformation between various external representations of the mathematical problems being addressed (Bichler et al., 2022; Hodds et al., 2014; Neuman & Schwarz, 2000; Renkl, 2017; Rittle-Johnson et al., 2017). Thus, in learning a concept or solving a mathematical problem, the mental process of self-explanation can act as a moderator or even a mediator for students' success in understanding and solving problems.

Regarding the importance of self-explanation in learning, Santosa et al. (2019) investigated the relationship between self-explanation and germane load. Germane load refers to the relevant cognitive load devoted to the process of acquiring knowledge from the information being learned (Costley & Lange, 2017; Debue & van de Leemput, 2014; Kalyuga, 2011; Paas & van Gog, 2006). Returning to the research by Santosa et al. (2019), to enhance self-explanation, worked-examples were designed with prompting in the form of questions to guide students in generating self-explanations at each step of the problem-solving process (Table 2 for example). The types of prompts developed were justification-based prompts and step-focused prompts (Conati, 2016; Hausmann & Chi, 2002; Hausmann et al., 2009). The study concluded that students who applied the worked-example method with self-explanation prompting achieved better test results compared to those who studied worked-examples without self-explanation prompting.

Table 2. Worked-example with prompting

No	Solution steps	Prompting
1	Suppose f is a piecewise function and suppose: $$f(x) = \begin{cases} 1, \text{if } 0 \le x \le 3, 0 \le y \le 1 \\ 2, \text{if } 0 \le x \le 3, 1 < y \le 2 \\ 3, \text{if } 0 \le x \le 3, 2 < y \le 3 \end{cases}$$ Calculate $\iint_R f(x,y)dA$ with $R = \{(x,y): 0 \le x \le 3, 0 < y \le 3\}$	Problems given.
2	Sketch of function: 	Can you explain and sketch the construction of the function?
3	Domain: $R_1 = \{(x,y): 0 \le x \le 3, 0 \le y \le 1\}$ $R_2 = \{(x,y): 0 \le x \le 3, 1 \le y \le 2\}$ $R_3 = \{(x,y): 0 \le x \le 3, 2 \le y \le 3\}$	Take notice to the origin area specified in the first step. How can this be obtained?
4	Double integral expression: $$\iint_R f(x,y)\,dA = \iint_{R_1} f(x,y)dA + \iint_{R_2} f(x,y)\,dA + \iint_{R_3} f(x,y)dA$$	Recall the double integral properties. What properties are applied in this step?

No	Solution steps	Prompting
5	Evaluating integral values: $= 1\,A(R_1) + 2\,A(R_2) + 3\,A(R_3)$ $= 1.3 + 2.3 + 3.3 = 18$	So, specifically, what does this step tell you?

Based on the explanation, individually, the worked-example approach undoubtedly enhances students' understanding of multivariable calculus concepts; however, further research is needed to explore its effectiveness in a collaborative (especially peer) learning context. In peer-collaborative learning environments without the use of worked-examples, studies have indicated improvements in learning outcomes. For instance, students learning statistics, geometry, algebra and calculus through interactive presentation styles, group work with discussions and feedback, and group presentations of solutions have shown positive effects on test results and academic success (Fauziah et al., 2022; Lugosi & Uribe, 2022; Ramadoni & Chien, 2023; Widodo et al., 2023). Another study found that students engaged in collaborative learning in calculus achieved higher graduation rates and developed better academic and movitation (Anitha & Kavitha, 2023; Fayowski & MacMillan, 2008). However, research by Merkel and Brania (2015) presents a contrasting view, claiming that the benefits of collaborative learning on learning gains and retention in calculus course have not been substantiated. Furthermore, research into peer tutoring (also in calculus course) has shown that most students tend to focus more on procedural and computational knowledge rather than conceptual understanding (Yaman, 2019).

In contrast to peer collaboration studies without worked-examples, research involving worked-examples in collaborative learning settings tends to yield similar conclusions: worked-examples are more effective in individual settings than in collaborative ones. In an initial study by Retnowati et al. (2010), while the results were statistically insignificant (close to significant), collaborative learning was suggested to offer potential benefits over individual learning when using worked-examples in a geometry theorem study. However, subsequent research failed to support this claim, demonstrating that individual learning outperforms collaborative learning with worked-examples (the material studied being algebra), firmly concluding that collaborative learning does not enhance the effectiveness of worked-examples (Retnowati et al., 2017). Similar findings have been reported in non-mathematical domains, such as biology (heredity), where individual learning proved more effective than collaborative learning in terms of cognitive efficiency, linking mental effort with test performance (Kirschner et al., 2009). A subsequent study (Kirschner, Paas, Kirschner, et al., 2011), also in the biology domain, corroborated this result.

Previous quantitative studies have consistently demonstrated that worked-example-based learning is more effective in individual contexts than in collaborative settings, particularly in enhancing cognitive efficiency and facilitating transfer of understanding. However, these studies predominantly focus on school-level learners, with limited exploration of higher education contexts, where learning dynamics are more complex. This research aims to validate the superiority of the individual learning over peer collaborative learning when studying with worked-example in higher education, particularly in the multivariable calculus course, by examining cognitive load dimensions and the quality of students' conceptual understanding. Furthermore, this study investigates the inherent limitations of peer collaboration in supporting the effectiveness of worked-example-based learning, aiming to provide empirical recommendations for designing instructional strategies better aligned with the demands of higher education.

2. METHOD

2.1. Research Approach and Design

The study employed a mixed approach to obtain a comprehensive picture of the limitedness of peer collaboration in understanding worked-example on multivariable calculus. This approach includes both quantitative and qualitative approaches. The quantitative aspect involved an experiment study that measured cognitive load and understanding of the concept learned and surveyed in peer collaboration, while the qualitative aspect analyzed group interactions and dynamics through discussion transcripts. The research design adopted in this study is a concurrent triangulation design (see Figure 1).

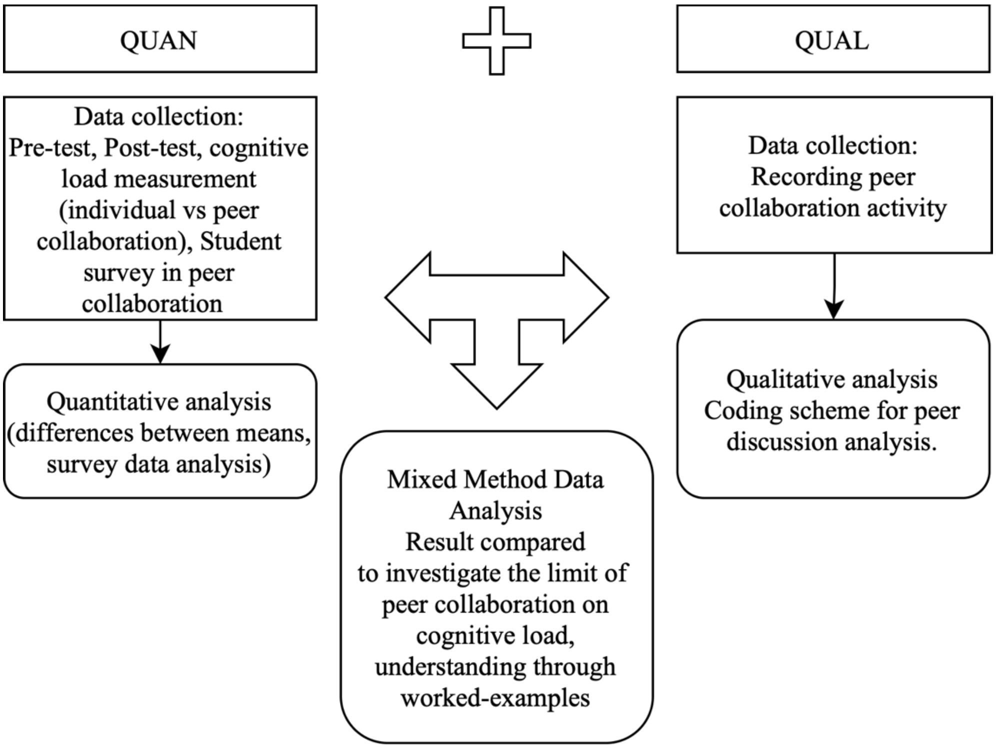


Figure 1. Concurrent triangulation design (Creswell & Clark, 2018)

2.2. Participants

One hundred thirty-one undergraduate students (41 boys and 90 girls) with an average age of 19.25 years old from a state university in Banten Province, Indonesia, took part in this research. The students were divided into two conditions, individual learning (52 students) and peer collaboration (79 students), which were assigned randomly. Students who learn peer collaboration were grouped randomly with 4 or 5 members (19 groups).

2.3. Research Instruments and Procedures

The research included three phases: a preparation phase, an implementation phase, and a data analysis phase. During the preparation phase, worked-examples on multiple integral topics were developed using materials sourced from textbooks compiled based on prior research (Santosa et al., 2024). Additionally, comprehension tests (pre-tests and post-tests) were designed to assess students' understanding after engaging with the worked-examples, rating scale mental effort for cognitive load measurement (Kester et al., 2010; Oktaviyanthi et al., 2024; Paas, 1992; Paas & Van Merrienboer, 1993; Tuovinen & Paas, 2004), surveys using questionnaires, and tools for recording discussions during peer collaboration were also prepared.

The implementation phase comprised four main stages. The first stage involved a pre-test (word problem) conducted before the intervention to assess students' initial understanding of the material. In the intervention stage, the experimental group studied worked-examples collaboratively in groups, while the control group completed the same tasks individually. Students worked on three worked-examples for each topic—double integrals over rectangular regions, iterated integrals, and double integrals over non-rectangular regions—within a 15-minute time limit per topic. All group discussions were recorded. Subsequently, a post-test (identical to the pre-test) was administered immediately after the intervention to evaluate students' final understanding, with test reliability determined using Cronbach's Alpha ($\alpha = 0.852$). Additionally, a nine-point subjective rating scale, was used to measure cognitive load after both the pre-and post-tests, with reliability results shown $\alpha = 0.820$ (see Table 3). At the end of the third test, students in the peer-collaborative condition completed a Likert-scale questionnaire (1 = strongly disagree to 5 = strongly agree) assessing aspects of engagement, effectiveness, confidence, feedback quality, and overall experience. Each aspect comprised three questions, with internal consistency reliabilities of 0.70, 0.66, 0.85, 0.79, and 0.65, categorized as high to very high.

Table 3. Rating scale mental effort

Scale	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Original version (English)	Very, very low	Very low	Low	Rather low	Neither low nor high	Rather high	High	Very High	Very, very high

In the data analysis stage, three main processes were conducted: quantitative data analysis, qualitative data analysis, and data integration. In the first stage, quantitative data analysis involved examining, analyzing, and interpreting data from pre-tests, post-tests, surveys, and cognitive load measurements. Statistical tests, such as descriptive statistics, and mean differences, were used to compare the experimental and control groups. The second stage focused on qualitative data analysis, which included transcribing recorded discussions and coding the data using thematic analysis (Braun & Clarke, 2006) to identify patterns in interaction and collaboration. This step included a review of the preliminary transcription to understand the conversational context within each group. Subsequently, the transcriptions were analyzed using both qualitative research software and manual techniques. A hybrid coding method was adopted, integrating inductive coding (identifying themes from the transcribed data) and deductive coding (deriving themes from theoretical frameworks and literature to address the research questions). The generated codes were managed, rechecked, and adjusted as necessary to support the development of a conceptual scheme for data categorization and re-categorization. Once the data categorization was completed, analytical insights were documented through memoing, which served to articulate and refine the analysis process. Key themes were identified during this stage to structure the data and derive meaningful results. These themes played a critical role in determining significant findings from the collected data. In the final stage, data integration was conducted by comparing and combining the results from the quantitative and qualitative analyses to draw comprehensive conclusions about the limit of peer collaboration when studying worked-example.

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Students' Pre-test Results

The pre-test was administered for each sub-topic, including double integrals over rectangular regions, iterated integrals, and double integrals over non-rectangular regions. The results indicated no significant differences in the pre-test score between the two class conditions (individual vs. peer collaboration) for double integrals over rectangular regions ($t_{stat} = 0.099$, $df = 129$, at $\alpha = 0.05$) iterated integrals ($t_{stat} = –0.173$, $df = 129$, at $\alpha = 0.05$) and double integrals over non-rectangular regions ($t_{stat} = 0.090$, $df = 129$, at $\alpha = 0.05$). The means and standard deviations of the pre-test scores are presented in Table 4.

Table 4. Means and standard deviations of pre-test and post-test

Condition	Pre-test			Post-test		
	1	**2**	**3**	**1**	**2**	**3**
Individual	18.38 (4.35)	15.79 (4.39)	18.81 (3.79)	86.15 (4.76)	81.96 (4.73)	83.31 (4.25)
Peer-Collaboration	16.87 (5.54)	15.91 (3.69)	18.75 (3.78)	77.16 (6.63)	82.33 (4.52)	77.95 (5.60)

1= double integrals over rectangular regions, 2=iterated integrals, 3=double integrals over non-rectangular regions

3.1.2. Students' Post-test Results

The post-test was conducted after students studied worked-example for each sub-topic, including double integrals over rectangular regions, iterated integrals, and double integrals over non-rectangular regions. The result revealed significant differences in the post-test scores between the two class conditions (individual vs. peer collaboration) for double integrals over rectangular regions ($t_{stat} = 8.441$, $df = 129$, at $\alpha = 0.05$) and double integrals over non-rectangular regions ($t_{stat} = 5.870$, $df = 129$, at $\alpha = 0.05$). However, no significant difference was found for iterated integrals ($t_{stat} = –0.447$, $df = 129$, at $\alpha = 0.05$). The means and standard deviations of the post-test are presented in Table 4.

3.1.3. Students' Cognitive Load Results

Cognitive load measurement was conducted immediately after students completed the pre-test and post-test. Regarding cognitive load during the pre-test, the results indicated no significant differences between the two class conditions (individual vs. peer collaboration) for double integrals over rectangular regions (t_{stat} = 0.286, *df* = 129, at α = 0.05), iterated integrals (t_{stat} = –1.323, *df* = 129, at α = 0.05), and double integrals over non-rectangular regions (t_{stat} = 0.410, *df* = 129, at α = 0.05). Similarly, for cognitive load during the post-test, the results showed no significant differences for double integrals over rectangular regions (t_{stat} = –0.274, *df* = 129, at α = 0.05) and iterated integrals (t_{stat} = –1.189, *df* = 129, at α = 0.05). However, a significant difference was found for double integrals over non-rectangular regions (t_{stat} = –8.118, *df* = 129, at α = 0.05). The means and standard deviations of cognitive load are presented in Table 5.

Table 5. Means and standard deviations of cognitive load ratings

Condition	Cognitive Load (Pre-test)			Cognitive Load (Post-test)		
	1	2	3	1	2	3
Individual	7.69 (1.11)	7.12 (0.78)	6.92 (0.81)	5.10 (1.40)	5.31 (1.13)	5.88 (0.78)
Peer-Collaboration	7.63 (1.12)	6.91 (0.79)	6.86 (0.86)	5.14 (1.38)	5.59 (1.15)	7.06 (0.82)

1= double integrals over rectangular regions, 2=iterated integrals, 3=double integrals over non-rectangular regions

3.1.4. Questionnaire

In the peer-collaborative class, students rated their perceptions of the peer collaboration process during worked-example learning across five aspects: engagement, effectiveness, confidence, feedback quality, and overall experience (see Table 6). For engagement, the most frequent response was 3 (neutral), with an average percentage of 69.33%. For effectiveness, the most frequent response was 2 (disagree), at 70.9%. For confidence, the most frequent response was 4 (agree), with an average of 58.7%. Regarding feedback quality, the most frequent response was 2 (disagree), at 65%. Lastly, for overall experience, the most frequent response was 2 (disagree), with an average of 44.7%.

Table 6. Students' perceptions in peer collaborative

Aspects	Questions	Responses* (%)				
		1	2	3	4	5
Engagement	I actively participate in group discussion.	-	12.7	68.4	19.0	-
	My peers encouraged me to contribute to the discussion.	-	22.8	67.1	10.1	-
	Our group stayed focused on task during most of the sessions.	-	7.6	72.2	19.0	1.2
Effectiveness	Peer collaboration helped me understand worked-example better than studying alone.	12.7	72.1	15.2	-	-
	Working with peers clarified difficult concepts in multivariable calculus.	8.9	78.5	12.6	-	-
	Group discussion exposed me to alternative problem-solving strategies.	21.5	62.0	16.5	-	-

Aspects	Questions	Responses* (%)				
		1	2	3	4	5
Confidence	I feel more confident solving multivariable calculus problem after the group session.	-	-	41.8	51.9	6.3
	Peer collaboration reduce my anxiety about tackling complex mathematicsal problem.	-	-	22.8	67.1	10.1
	I feel more comportable explaining mathematical concepts to others after these session.	-	2.5	31.6	57.0	8.9
Feedback Quality	My peer provided constructive feedback during discussion.	7.6	65.8	25.3	1.3	-
	The feedback from my peers helped me correct my mistakes.	2.5	69.7	27.8	-	-
	Our group provided a supportive environment for learning and discussion.	5.1	59.5	35.4	-	-
Overall Experience	I would recomend peer collaboration for learning mathematical concepts using worked-example.	-	10.1	72.2	17.7	-
	Peer collaboration should be integrated as a regular activity when learn by worked-examples.	17.7	64.6	17.7	-	-
	My overall experience with peer collaboration was positif when studying worked-examples.	17.7	59.5	22.8	-	-

*1 = strongly disagree to 5 = strongly agree

3.1.5. Peer Discussion Analysis

Based on the transcription data obtained from the recoding of students' conversations in each peer discussion group, five major categories with distinct subcategories emerged, as presented in Table 7.

Table 7. Coding scheme with categories and subcategories data (% frequency)

Categories	Subcategories (% frequency)	Description
Collaboration Modality: *How students interact in peer when comprehending worked-example*	1. Individual Processing (0)	Students read independently without any interaction.
	2. Passive Aggrement (10.52)	Students only agree without providing new information.
	3. Surface Level Discussion (47.37)	Students discuss the worked-example but merely repeat the available information.
	4. Misguided/ Elaborative Discussion (42.11)	Students discuss the worked-example, which either lead to misconceptions or, in rare cases, result in deeper interpretations.
Cognitive Engagement: *To what extent students are cognitively engage in understanding the worked-example*	1. Minimal Engagement (5.26)	No significant cognitive activity is demonstrated; students merely read without effort to deeply understand the content.
	2. Redundant Processing (52.63))	Students repeat the content of the worked-example without providing further analysis.
	3. Effortful Understanding (42.11)	Students attempt to understand by asking questions or rephrasing the content with slight additional thoughts.

Categories	Subcategories (% frequency)	Description
	4. Deep Understanding (0)	Students demonstrate deeper understanding by connecting worked-example (a rare occurence).
Interaction Quality: *The quality of interaction in discussion on the worked-example*	1. Minimal Interaction (36.84)	No meaningful discussion occurs; students merely read together without further exploration.
	2. Redundant Interaction (10.53)	The worked-example is repeated without any addition of new information.
	3. Clarification Seeking (52.63)	Students ask questions to clarify their understanding due to confusion.
	4. Constructive Interaction (0)	The discussion provides additional insight beyond those presented in the worked-example (a rare occurence)
Cognitive Load: *The cognitive load arising from collaboration in understanding the worked-example*	1. Underload (57.89)	Students do not face challenges in understanding and feel no to engage in discussion.
	2. Optimal Load (0)	Discussion is utilized to explain difficult parts.
	3. Extraneous Overload (42.11)	Discussion hampers understanding as the information from the worked-example is already sufficiently clear.
	4. Intrinsic Overload (0)	Student continue to struggle with comprehension despite the presense of the worked-example
Effectiveness of Collaboration: *To what extent collaboration enhances students' understanding of the worked-example*	1. Innefective (57.89)	No additional benefit is gained from the discussion
	2. Partially Effective 42.11)	Some clarification is provided, but it does not significantly enhance understanding
	3. Effective (0)	The discussion helps improve understanding of the worked-example (a rare occurence)

Collaboration Modality

Based on the collaboration modality category, when students studied the worked-example, it was identified that they only agreed without contributing new information (passive agreement). Students discussed the worked-example but merely repeated the available information (surface-level discussion). In some cases, discussions led to misconceptions (misguided discussion).

Example conversation:

Student 1 : *"So in this worked-example, we are asked to calculate a triple integral with boundaries x from 0 to 2, y from 1 to 3, and z from 0 to 4."*

Student 2 : *"Yes, it means that we can immediately integrate it with first x, then to y, then to z, right?"*

Student 3 : *"Wait, aren't we supposed to always start from the outer integral to the inner one? So we should begin with z first, then y, and finally x?*

Student 4 : *"Yeah, it seems like it has to be in that order, from the outer to the inner integral, and it can't be switched."*

(Misconception – the student incorrectly assumes that order of integration must always proceed from the outer to the inner integral without considering the given limits)

Student 1 : *"But the boundaries have been determined in the question, we can't arbitrarily change the order, you know."*
Student 2 : *"Yes, but if we start from the outer integral first, the result will be correct in the end."*

(Misguided Discussion – the discussion leads to a misconception, disregarding the flexibility in choosing an appropriate order of integration)

Student 3 : *"As far as I know, we can't change the order, otherwise the result will be completely different!"*
Student 4 : *"Okay, then let's jus follow this method. Start with the outer integral first to be safe"*

(The discussion concludes with an unclarified misconception, reinforcing the misunderstanding)

This conversation illustrates how misconceptions in group discussions can lead to incorrect understanding, particularly when no group members is able to correct or clarify incorrect/inaccurate information

Cognitive Engagement

Under the cognitive engagement category, students demonstrated minimal engagement by merely reading without making efforts to understand deeply (minimal engagement). They repeated the worked-example without further analysis (redundant processing). However, there were instances where students attempted to understand by asking questions or re-explaining with slight additional thoughts (effortful understanding).

Example conversation:

Student 1 : *"Wait, this step looks complicated. Why do we need to use this method?*
Student 2 : *"Hmm... maybe it's because the problem involves variables similar to those in the worked-example."*
Student 3 : *"But look at the second example. There's another method used for a different case."*
Student 4 : *"Oh, I see. So, if the conditions change, the method changes too."*
Student 1 : *"Exactly! Now, let's check the final result."*

This dialogue illustrates effortful understanding as students engaged in deeper questioning and reasoning.

Interaction Quality

The quality of interaction during peer collaboration showed minimal engagement, with students merely reading together without further discussion (minimal interaction). They repeated the worked-example without adding new insights (redundant interaction). In some instances, students sought clarification due to confusion (clarification seeking).

Example conversation:

Student 1 : *"Ok, in this worked-example, we compute the triple integral. In the first step, we define an integral boundary for each variable"*
Student 2 : *"Yes, the limits for x are from 0 to 2, for y from 1 to 3, and for z from 0 to 4."*
Student 3 : *"Okay, it means that we just have to integrate it step by step: integral to z, then to y, finally to x."*

Student 4 : *"Yes, just like it's shown in the worked-example." (Redundant interaction - merely repeating without adding new insight)*

(After a while, the discussion shift to Clarification Seeking as one of the students notices a discrepancy in their result)

Student 3 : *"Wait, why is the final result different from the one in the worked-example?"*
Student 2 : *"Let's check again. There may be a mistake in the first integration step?"*
Student 1 : *"Oh, it seems like we forgot to notice that this function depends y on as well. We should take into account variables y before integrating with respect to x."*
Student 4 : *"Right! That means we need to be careful aout the order of integration based on the given limit."*

(Clarification Seeking – students actively seek clarification regarding their mistake)

Student 3 : *"Okay, now it makes sense. If we change the order of the integrations, our result matches the worked-example!"*

At the beginning of the discussion, the students merely repeated the steps from the worked-example without providing additional new understanding. As a result, there was no in-depth analysis, only agreeing to the steps that have been written (redundant interaction).

Cognitive Load

The cognitive load generated from collaboration revealed two conditions. In some cases, students did not experience any challenges, feeling no need for discussion (underload). In others, discussions overloaded understanding due to the clarity of the information provided in the worked-example (extraneous overload).

Example conversation:

Student 1 : *"So, the integral bounds are from 0 to 2 for x, and 0 to 3 for y, right?"*
Student 2 : *"Yes, just integrate according to the steps in the worked-example."*
Student 3 : *"Alright, substitute the function into the integral. That's it, right?"*
Student 4 : *"Yes, there's no need for a long discussion. It's straightforward."*

After a while, the discussion shifted to irrelevant topics:

Student 2 : *"What if we change the upper bound to a different function, like sin x?"*
Student 1 : *"Why would we do that? It's not in the problem."*
Student 4 : *"Exactly. Changing the bounds would give a different result."*
Student 3 : *"Still, it would be interesting to explore other forms, although now we're confused."*
Student 4 : *"Yeah, it's getting complicated. Let's just stick to the problem."*

Effectiveness

In terms of learning effectiveness, peer discussions during worked-example learning were identified as either ineffective or partially effective. Some clarification occurred but did not significantly enhance understanding (partially effective).

Example conversation:

Student 1 : *"For this problem, we just need to follow the worked-example, right? Integrate from 0 to 2, and that's it."*

Student 2 : "Yes, it's not difficult. Just apply the formula."
Student 3 : "Right, but why does a constant appear in the final result?"
Student 1 : "Hmm... maybe it comes from the integral bounds. I'm not sure."
Student 4 : "Check the worked-example. It explains that the constant comes from the inner integral result."
Student 3 : "Oh, so the inner integral already gives a constant before moving to the next stage."
Student 2 : "Exactly. That's why the final result includes that constant."
Student 4 : "Now I understand. Changing the bounds would also change the final result."

This dialogue illustrates partial effectiveness in clarifying understanding.

3.2. Discussion

The study findings reveal no significant differences in pre-test results between the individual and collaborative conditions across topics (double integrals over rectangular regions, iterated integrals, and double integrals over non-rectangular regions), with both groups demonstrating low achievement. This indicates that students possessed limited prior knowledge regarding these topics, suggesting an equivalent baseline of knowledge between the two conditions. In contrast, post-test results showed a substantial improvement after students engaged with worked-examples, indicating the positive impact of this instructional method. This aligns with the well-documented worked-example effect, supported by over 25 years of research. The effect has been extensively demonstrated in well-defined problems such as mathematics and science and more recently in ill-defined domains like language and music (Diao & Sweller, 2007; Oksa et al., 2010; Owens & Sweller, 2008; Rourke & Sweller, 2009).

Although both conditions experienced significant post-test improvements, individual learners outperformed those in peer collaboration groups. Topic-wise, the only exception was the iterated integrals topic, where no significant difference was observed. For double integrals over rectangular and non-rectangular regions, the individual condition showed superior performance. These findings confirm prior studies suggesting that learning worked-examples individually yields better results than peer collaboration (Kirschner, Paas, Kirschner, et al., 2011; Retnowati et al., 2017).

In terms of students' cognitive load, no overall differences were found between the individual and peer collaboration groups in worked-example learning. When analyzed by topic, a significant difference was observed only in the double integrals over non-rectangular regions topic, while no differences were found for double integrals over rectangular regions and iterated integrals. These findings validate previous research, which also reported no significant differences in cognitive load between individual and peer collaboration learning conditions (Kirschner, Paas, & Kirschner, 2011; Retnowati et al., 2017).

Furthermore, this study was not solely aimed at validating the effectiveness of worked-example learning or the superiority of individual learning over peer collaboration. Instead, it sought to investigate the limitations of peer collaboration in studying worked-examples. The questionnaire revealed that out of five aspects assessed (engagement, effectiveness, confidence, feedback quality, and overall experience), only the confidence aspect was positively perceived by students during peer collaboration. Students reported increased confidence in solving multivariable calculus problems after group sessions, reduced anxiety (particularly with complex problems) and greater comfort in explaining mathematical concepts to others. However, these positive perceptions did not extend to the other aspects: engagement, effectiveness, feedback quality, and overall experience.

The limitations of peer collaboration were further examined through peer discussion analysis. Findings from peer collaboration in worked-example learning revealed significant challenges in achieving collaborative learning effectiveness. Based on a coding scheme comprising collaboration modality, cognitive engagement, interaction quality, cognitive load, and collaboration effectiveness, the results indicated that collaboration was generally ineffective or only partially effective under most circumstances. A detailed analysis of these findings follows, highlighting the factors contributing to the limitations of peer collaboration in the context of worked-example learning.

In the collaboration modality category, most interactions were characterized by passive agreement and surface-level discussion, where students simply followed the worked-example without meaningful engagement, easily agreeing with their peers and participating in redundant discussions. This type of collaboration limited opportunities for knowledge construction, resulting in minimal reasoning and restricted critical thinking. Additionally, misguided discussions emerged, where students deviated from the task's objectives with unnecessary discussions, adding complexity that undermined the collaboration process. These findings indicate that collaboration modality often fails to stimulate meaningful engagement, particularly when students rely too heavily on the information already provided in the worked-example. This observation aligns with previous research suggesting that peer collaboration offers limited benefits when the task structure is highly guided (Kirschner et al., 2006).

The second category, cognitive engagement, varied across groups, ranging from minimal engagement and redundant processing to, in some cases, effortful understanding. Minimal engagement occurred when students perceived the task as too easy and required little to no mental effort. This aligns with the condition known as underload, where students found no need for deeper reflection or critical thinking regarding the material being studied. In such cases, engagement was superficial and did not support meaningful learning. Conversely, effortful understanding was observed when students sought clarification on specific aspects of the worked-example, such as determining the bounds for double integrals. Although this behavior indicated increased cognitive effort, it did not consistently lead to comprehensive conceptual understanding. The students' efforts often remained focused on procedural clarity rather than on constructing deeper insights or reorganizing their existing knowledge structures. This highlights a key limitation in worked-example-based collaboration: while certain interactions can promote cognitive engagement, they may not always be sufficient to foster higher-order understanding without additional instructional scaffolding.

Third, the category of interaction quality was predominantly characterized by either minimal or excessive interaction, with limited instances of clarification seeking or constructive interaction. Minimal interaction occurred when students engaged with the worked-example without further elaboration or exploration. Conversely, excessive interaction involved repeatedly following procedural steps outlined in the worked-example, indicating no additional learning value from the collaborative process.In contrast, clarification seeking was observed when students attempted to address misunderstandings related to specific elements in the worked-example, such as determining the integration bounds. This behavior suggests that, while peer collaboration can promote clarification, it may not consistently lead to deeper conceptual understanding if limited to surface-level questioning. These findings underscore the need for collaborative tasks that encourage more meaningful and reflective engagement to optimize learning outcomes.

The next category, cognitive load, revealed two contrasting conditions: underload and extraneous overload. In many groups, underload occurred when students perceived the problem as straightforward and solvable through linear steps, leading to disengagement and passive agreement. This lack of challenge reduced opportunities for meaningful collaboration, as students felt that discussion was unnecessary. Conversely, extraneous overload emerged when students overcomplicated the task by proposing irrelevant modifications to the worked-example. This excessive cognitive load hindered learning by diverting students' attention from the primary objectives. These findings support cognitive load theory, which posits that collaboration can become counterproductive when extraneous cognitive demands exceed students' working memory capacity (Sweller et al., 1998).

The final category, collaboration effectiveness, was predominantly characterized by ineffectiveness. Collaborative learning was ineffective when students merely followed the procedural steps outlined in the worked-example without gaining any new insights. In contrast, partial effectiveness was observed when students engaged in clarification seeking and partial elaboration of key concepts. However, these efforts were often insufficient to produce significant learning gains (van Merriënboer & Kirschner, 2017).

These findings underscore the importance of designing collaborative learning activities that strike a balance between cognitive load and deeper, more meaningful engagement. While worked-examples are effective in reducing cognitive load in individual learning, their structured format may not fully support collaborative learning. This limitation arises because highly guided tasks often leave little room for active exploration or co-construction of knowledge within a group setting. However, the effectiveness of collaborative learning could be enhanced through the integration of complementary tasks that promote problem-solving and active reasoning. Such tasks can provide opportunities for students to engage in dialogue, share perspectives, and collaboratively apply concepts to more complex scenarios. Additionally, modifying the structure of worked-examples (by incorporating prompts that require reflection, inquiry, or multi-step problem-solving), may further improve the effectiveness of peer collaboration by fostering cognitive engagement and encouraging deeper processing of the material.

4. CONCLUSION

Although worked-examples proved effective in teaching multivariable calculus concepts in terms of both knowledge acquisition and cognitive load, peer collaboration often faced limitations due to underload, redundant interaction, and ineffective collaboration modalities. However, opportunities for effortful understanding and clarification seeking indicate that collaboration can still play a supportive role if instructional design encourages deeper engagement and problem-solving. Future research is needed to explore strategies for optimizing peer collaboration in guided learning contexts through manipulations of worked-examples, cognitive load, and task complexity.

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