MODESTUM

EURASIA Journal of Mathematics, Science and Technology Education, 2025, 21(1), em2557
ISSN:1305-8223 (online)

OPEN ACCESS

Research Paper

https://doi.org/10.29333/ejmste/15794

Learning mathematics through peer assessment: "How can we assess something that we ourselves don't know how to solve?"

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Received 21 October 2024 ▪ Accepted 10 December 2024

Abstract
The study explores the opportunities for learning mathematics when students engage in peer assessment. This paper is the result of a study that took place at the Center for Pre-University Education of the Technion–Israel Institute of Technology. The participants were enrolled in a single-semester preparatory course in mathematics to reach level-five-matriculation proficiency. Data was collected using video cameras and audio recorders, among other methods, to capture students' interpretation of diverse mathematical content and ideas. I identified important thinking skills that included, but were not limited to, deciphering solutions, comparing ways of tackling problems, and differentiating criteria that were occasioned by direct student-student interaction during which they continually clarified their mathematical insights, ideas, queries, and hunches. The contribution of this particular study lies not only in the light it sheds on the benefits of peer assessment for learning purposes but also on identifying occasioned moments of learning mathematics as they occurred in such contexts.

Keywords: peer assessment, learning, developing criteria, effect student learning, preparatory course, learning mathematics

INTRODUCTION

Theoretical Background and Literature Review

A crucial question when researching problem-solving in mathematics is what students can learn while engaging in collaborative problem-solving (Klang et al., 2021). Our study focuses on the question of what the act of peer assessment contributes to students' knowledge regarding the problem-solving procedure.

Since the 1990s, there has been a shift in the approach to student assessment that manifests itself, in some countries, by shying away from the teacher-centered framework–that is to say, a "tell-show-do" approach and summative-oriented assessment–to a student-centered framework that employs a more distributed approach to teaching and assessment and that aims to accommodate students' different needs (Bedford & Legg, 2007; Black & Wiliam, 2006; Birenbaum, 1996; Dori, 2003). I dubbed this as a shift from an "era of testing" to an "era of assessment". This shift has generated a need for alternative assessment methods, often defined as "formative" and "educative assessment". Henning et al. (2012) designed both to promote and gauge learning (Black & Wiliam, 1998). Similarly, Schoenfeld (2002) sums up the underlying sensibility of alternative assessment: "[A]lternative assessments should be provided where test results may not provide accurate reflections of students' abilities … [alternative] assessments should cover the broad spectrum of content and thought processes" (p. 24). Indeed, according to Strijbos and Sluijsmans (2010), the move to an alternative assessment culture is highly beneficial, as it serves both summative and formative purposes. In particular, this is because formative assessment becomes part of the learning process: it takes place not only once but several times over the duration of a course or academic school year; it focuses on a multitude of learning aspects, such as cognitive, social, affective, and meta-cognitive ones; and it enables teachers to attain a fuller, multi-layered profile of their students, something that cannot be manifested by a single score. Alternative assessment methods include peer assessment, co-assessment, and

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Contribution to the literature

- This study contributes to existing literature by demonstrating the practical benefits of peer assessment in a mathematics learning context.
- It highlights how peer feedback, as an integral part of the learning process, enhances both understanding and critical thinking.
- The research also addresses gaps by providing empirical evidence on how peer assessment impacts student engagement and responsibility in collaborative settings.

self-assessment, all of which promote integrating assessment with instruction and all of which view the student as an active participant who "shares responsibility, reflects, collaborates and conducts a continuous dialogue with the teacher" (Dochy et al., 1999, p. 331).

Peer assessment in a learning environment is becoming an increasingly used tool. This study took peer assessment into the mathematics classroom. It focused on both the mathematical content and the interactions that take place during a peer assessment activity. Its aim was to shed light on the overall benefits of peer assessment in the context of learning mathematics while pointing out occasioned moments of learning with respect to specific mathematical concepts.

Learning processes are enhanced with the addition of peer (i.e., collaborative) assessment, as this provides spaces for collaborative learning. Pain and Mowl (1996) argue that "collaborative assessment" applies to a situation in which an "assessor" and an "assessee" discuss a solution to reach a mutual understanding of each other's hunches, ideas, or queries. Furthermore, if the two parties share the goal of providing assessment, conditions for collaboration are set. Both parties learn from the process of ironing out differences and changing their roles from student to teacher and back to student.

Topping (2017) describes peer assessment as a form of engagement where students judge a peer's performance quantitatively by scoring or grading and/or qualitatively by providing written or oral feedback. A study by Li et al. (2020) found that alongside empirical evidence regarding the effect of peer assessment on learning, there is considerable theoretical support to suggest that it promotes student learning which indicates that its benefits are multi-faceted.

Strijbos and Sluijsman (2010) qualify and extol peer assessment as "an educational arrangement where students judge a peer's performance … and which stimulates students to reflect, discuss and collaborate." (p. 1). It "encourages involvement, … promotes excellence, provides increased feedback, fosters attendance and teaches responsibility" (Weaver & Cotrell, 1986, p. 25). Furthermore, it may be seen as an opportunity for increased involvement, responsibility, and accuracy because of considerations that students generate when they assess the points of a problem they are reviewing and their need to be fair and accurate when judging their peers (Keaten & Richardson, 1993).

It is commonly assumed that students who solve the same problem simultaneously encounter similar difficulties, thus making their explanations to their peers more catered to and more focused on the points which are more difficult to understand (Strijbos & Sluijsmans, 2010). It is also contended and empirically proven that the contribution of peer teaching is not only to the receiver of the explanation but to its giver too, because they clarify for themselves points which they might not have been aware of had they not explained them to their peers (Webb, 1991).

Despite this realization, there is a dearth of research that focuses on peer assessment in the context of mathematics. I wish to remedy this lacuna by showing how the inclusion of peer assessment activities can offer opportunities for learning.

The issue of peer feedback has received broad treatment lately in the work of scholars such as Cho and MacArthur (2010), Gielen et al. (2010), Strijbos et al. (2010), and Van Steendam et al. (2010), who have reported that focused feedback may lead to better academic performance. In addition, it has been reported that in certain cases, peer feedback is even more significant for the evaluatee than that given by the teacher (Pain & Mowl, 1996).

Kollar and Fischer (2010) have claimed that contexts in which assessors and assessees can interact during the assessment itself might lead to significant learning. In addition, these interactions might be viewed as an answer to a dilemma presented by them:

> Ultimately, highly interactive variants of peer assessment may have both advantages (e.g., through evoking high-level argumentation) and disadvantages (e.g., through interrupting individual thought processes) for learning. It is certainly a task for future research to investigate under which circumstances more interactive variants of peer assessment should be preferred over less interactive ones and vice versa (p. 4).

Mathematics Learning Through Discourse in Peer Assessment Activity

The mathematical language manifested during the process of student-student peer assessment, which may be termed "languaging," is also an important aspect associated with assessment methods (Henning et al., 2012). Cobb et al. (1993) posited that proper languaging can facilitate the development of mathematical proficiency. It is thus not surprising that the National Council of Teachers of Mathematics (2009) stated the following:

> Through communication, ideas become objects of reflection, refinement, and discussion … The communication process also helps build meaning and permanence for ideas … When students are challenged to think and reason about mathematics and communicate the results of their thinking with others, they learn to be clear and convincing in their verbal and written explanations (p. 2).

Mercer (2005) corroborates this and notes that the languaging that takes place during peer assessment activities contributes to the development of conceptual understandings in mathematics. The scope of influence of such discourse may be expanded to include its contributions to the negotiation of shared meaning (Moschkovich, 1996, 1998), the formation of mathematical generalizations (Ellis, 2011), and the development of mathematical identity (Bishop, 2012)

The current study followed the mathematical discourse from the moment the students sat in groups and discussed the criteria for evaluation and the evaluation of the products they received to evaluate. Sfard (2012), relates to mathematical thinking and mathematics proper as to discourse. Thus, mathematical thinking means to communicate mathematically with others or oneself.

The view of mathematics as discourse dictates the definition of learning: if mathematics is mathematical discourse, it follows that learning is a broadening of this discourse and its evolution. Teaching mathematics is, then, a process of discourse development which includes mathematical discourse of the individual. However, not every discussion about mathematics is also a learning opportunity.

As the discourse progresses, the use of words, mediators, and other utterances commonly used in mathematical discourse changes. Moreover, as the discourse develops, we may notice a change from ritual routines- which emphasize the final outcome, or perceived mistakes as a source of embarrassment, to a routine of inquiry–attempt to find different and varied ways to the solution, the ability clarify and explain. At every stage I analyzed how the discourse between the assessors developed, particularly concerning their progress in evaluating the materials they were asked to assess. In order to create mathematical objects in the discourse, they must be discussed. The only way to do so would be to start by taking the utterances of an experienced participant.

As already stated, initially, the participants used rituals resulting from imitating other participants in the discourse, and finally, there was investigative participation where the interlocutors participated independently in the discourse (Sfard, 2012, 2021).

Harel and Koichu (2010) define learning as "a continuum of disequilibrium-equilibrium phases manifested by (a) intellectual and psychological needs … [and] by (b) ways of understanding or ways of thinking that are utilized … during these phases" (p. 11). Disequilibrium occurs when students encounter an obstacle, and they try to find a way or ways to remove or surmount it; students achieve equilibrium when they successfully overcome that obstacle. This definition is an operative one, as it suggests a method to examine the process by which students make sense of mathematics in the context of peer evaluations.

Research Questions

Our focus in this investigation was to explore what benefits peer assessment offers in providing occasioned moments of learning in mathematics. I do this by highlighting students' forms of meaning-making guided by the following research questions:

1. How does peer assessment foster student involvement and responsibility in learning?
2. What do students learn from their interlocuter's solutions when acting as assessors?

METHOD

Research Locale and Participants

The study took place at the Center for Pre-University Education of the Technion–Israel Institute of Technology. The participants were students in two classes (approximately 30 students each) of an intensive, single-semester preparatory course in mathematics to bring them up to level-five-matriculation proficiency[1]. Such preparatory courses are offered in many universities worldwide to close any gaps between students' achievements in high school and prerequisites for academic study. Typically, their progress is systematically assessed using traditional methods, i.e., exams, but during the course, students worked in groups and were asked to assess their peers' work. Six such peer assessment activities (three from each class) were recorded using a video camera and audio recordings[2].

[1] Such preparatory courses are offered in many universities worldwide to close any gaps between students' achievements in high school and prerequisites for academic study.
[2] The study took place in Hebrew and transcripts were translated for this study.

$f(x) = \frac{\cos x}{\sin^2 x}$ is a function at $-\frac{\pi}{2} \leq x < 0$.

1. Find all the asymptotes, if any, which are parallel to the axes.
2. Find the points of intersection, if any, of the function with the axes.
3. Prove that the function is increasing.
4. Find the equation of the tangent to the graph of $f(x)$ at its point of intersection with x-axis.
5. Find the area of the figure constrained by $f(x)$, the above tangent, and $x = -0.5$.

Figure 1. Sample problem (Source: Field study)

Procedure

Each of the six peer assessment activities was 90 minutes long. In the first stage (25 minutes), the students were asked to individually solve a mathematical problem randomly chosen from the course textbook (see **Figure 1** for a sample problem).

In the second stage (15 minutes), the students were randomly divided into groups of two or three and asked to formulate criteria for the evaluation of the other students' solutions to the problem and to weigh the criteria according to their relative importance. Each group was given a four-page booklet: they were to write their evaluation criteria on the first page and use the remaining pages to comment and score the other students' solutions.

For the third stage (50 minutes), each group received the solutions of three other students for assessment. This was not anonymous (i.e., all the students knew whose solutions they were reviewing and who was checking theirs). Inter-group conversation was allowed and encouraged at all stages of the activity.

The students were advised that this was merely an exercise, and their assessment would not affect their peers' final marks. This was to prevent them from feeling inhibited about giving a bad mark or comment.

In the fourth stage, the annotated work was returned to the assessees who were given the opportunity to respond, either to explain their work or question the assessment if they disagreed with it (see **Figure 2** for a summary of the four stages).

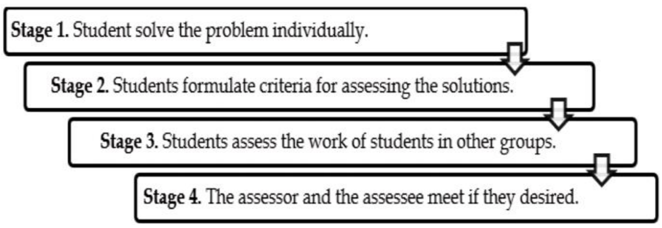

Figure 2. Stages in peer assessment activity (Source: Authors' own elaboration)

Designing peer assessment activities for this study

How to design peer assessment activities emerges from the way the students engaged in social interaction, took responsibility, and depended on each other. The nature of the activity provided the learners with learning situations in which they were given roles which required giving explanations and asking questions together with their role as learners- the need to learn about the right solution to the problem and to assess it appropriately. These settings evoked discussion and active listening while conducting the phases of the assignment. The students in each group were chosen at random, yet it appears that this allowed them to learn from each other, help each other, and enrich each other. The environment created was conducive to active involvement in the assessment assignment. Each student was able to show their skills and to contribute their knowledge to the group. This social interaction in collaborative learning which exposes the student to multiple perspectives and an exchange of knowledge among the members of the group is known to have a positive impact on the learner's achievements (Kollar & Fischer, 2010; Leikin & Zaslavsky, 1999; Radford, 2011).

Together with the advantages of collaborative learning for the learner, there are also challenges to integrating peer assessment in the curriculum. However, by designing peer assessment activities along the lines of this study, these difficulties may be overcome (Balacheff, 1991).

> **First challenge:** As part of a collaborative group, the student needs to work as part of a team throughout. They may feel pressured by the group yet cannot distance themselves and express themselves through a personal product that characterizes them.

As stated above, the members of the collaborative groups were first told to solve the assignment on their own, staged as a kind of test writing. This stage contributed to the discourse between the assessors, since each assessor brought their own position concerning the choices of solving the problem they had been given and had had time to work these out as they solved the problem on their own. They may have encountered difficulties or seen how others might encounter those. This level enabled brainstorming which came to the fore both in the stage where criteria for ranking (solutions) were set, as well as when they discussed their reservations concerning how right or wrong the solutions they checked were.

> **Second challenge:** The small collaborative group reduces the students' average to that of the group. The need for conformity in the group mainly

harms the gifted student and limits the latter's thinking skills and creativity.

Similar to other studies on collaborative learning that point to group heterogeneity as an effective tool for enhancing collaborative learning (Davidson, 1990; Johnson & Johnson, 1985), I observed that when groups were composed of students who succeeded in solving the assignment, and those who could not solve the problem on their own, the heterogeneity paid off, as students who had succeeded in solving the problem correctly, or those who had only partly succeeded, very quickly took on the role of teacher within the peer assessment group and started to answer their peers' questions concerning the solutions they checked. This situation of one member of the group explaining to their peer is well-known and is also supported in the literature. On the one hand, the act of explaining sheds light on aspects of which the explainer themself had been previously unaware, while on the other hand, the student gets a better understanding of what was unclear to their peers. They speak a common language which helps the person getting the explanation to gain a better understanding when needed (Webb, 1991).

Third challenge: In a collaborative setting, weak, lazy, or uninterested students get the benefit of the diligent students, and in this way they relinquish the responsibility for their own learning.

As part of the exploratory study, various options for conducting the peer assessment tasks were tried. One of them was a situation where a single student solves the problem, and another assesses it. Here I noticed that students who failed to solve the problem on their own refrained from taking part in the peer assessment, claiming that they could not assess a solution they had failed to find. The phenomenon of social avoidance concerning collaborative learning is well known in literature (Kerr & Tindale, 2004). However, the present study did not observe this phenomenon as a finding. In the documentation I noticed that students who had had difficulties solving the assignment in the initial, individual phase, took an active part in the self-assessment phase, e.g., by asking questions of the group members; making attempts to probe deeper and to understand the phases of the solution offered, and then, later, to take a stand on its validity, and even voicing their opinions concerning the grade they had to give.

In this study, peer assessment was done openly: the fear of exposure and personal hurt; the fear of hurting one's peers, and the difficulty of being objective, are well-known in the literature on peer assessment. This study did not average the grades resulting from the peer assessment into the formal ones, and so, these fears did not worry the students, as can be seen in the study's findings. It must be noted that the participants in this study did state concerns about averaging in their assessment as part of the formal one. Once these were allayed, students initiated assessor-assessee meetings spontaneously, but the added learning discourse they created has not been elaborated upon in this study.

Data Sources

Three video cameras and four audio-recording devices were placed at strategic spots throughout the room to enable simultaneous observation (both visually and audially) of the students' collaborative work (second and third stages of the activity) and to capture student interactions, both between the assessors (i.e., within groups) and between the evaluators and assessees (based on Maher & Martino, 2000). The students quickly disregarded the existence of the recording equipment. The recording devices made it possible to explore students' languaging as they were engaged in mathematical meaning making. A total of 12 video recordings and 13 audio recordings were collected over the duration of the six assessment activities analyzed. All the solutions to the task and evaluation notes were collected at the end of the activity.

After the students had completed the evaluation process, semi-structured interviews were conducted with eleven randomly chosen students. The interviews were in Hebrew (the students' native language), were conducted on campus and lasted 30 minutes on average. Questions were prepared in advance to ascertain their opinions regarding their experience of evaluating their peers, the types of difficulties they had faced, and their feelings regarding the learning potential of such a process.

Data Analysis

The video and audio recordings were transcribed, and the written documentation (booklets and evaluation sheets) collected. Analysis suggested three recurring aspects:

(1) negotiations to decide on criteria,

(2) discussions regarding the solutions of the assessees and scoring, and

(3) discussions between the assessors and the assessees.

The next stage consisted of comparing the assessors' solutions, before they assessed their fellow students' work, with the assessments of their peers. This allowed us to observe what learning opportunities had taken place, by observing how their understanding of the problems changed over time. Finally, I analyzed the transcriptions with a focus on finding learning opportunities that emerged from the activity.

First, the participants' notebooks (assessors and assessees) were examine to identify the type of mathematical language used by each.

The mathematical language initially used in their own solutions and that used during their evaluations were compare to see if the process had made any contribution to enhance their understanding and languaging. The booklets also enabled further analysis of the mathematical content relating to the assessors' attempts to elucidate and assess the assessees' solutions.

Data analysis was conducted using the thematic analysis approach. During the review of the group discussion transcripts, both those from when the students were formulating evaluation criteria and those from when the students were assessing the outputs based on those criteria, excerpts were identified that shed light on each stage the group underwent. These excerpts were then categorized into emerging themes through a bottom-up process aimed to identify intriguing phenomena within the data. This process revealed patterns and varying contexts of improvisation.

Examination of video and audio recordings

The recorded data allowed us to observe students explaining the solution method to each other, bouncing ideas, discussing hunches, delving into queries, identifying mistakes, and positing the sources of these mistakes. In general, during the peer assessment activities, students had the chance to consider solution methods which differed from those which they had used, whether based on a different method entirely or how the solutions were qualified (for instance, skipped or additional stages, explanations, etc.). This exposure forced students to delve deeper into the problem to understand this different solution method and assess it.

As mentioned, the groups of three were formed completely at random, so it is reasonable to assume that they were heterogeneous with respect to background knowledge and proficiency in mathematics. Therefore, students who understood the mathematical problem more easily became the teacher and began to explain the solution process to the others.

There were some instances of disagreement regarding the correctness or incorrectness of the solution being discussed or when assessors raised different contentions concerning the solutions presented. There was often much disagreement regarding the grades and their validity. For the most part, students were adamant regarding the grade to be awarded, and this enriched the mathematical discourse.

A three-phased focused content analysis (Hsieh & Shannon, 2005) was carried out as follows: Phase one included the transcribed discussion among the students while they perused the documents at their disposal, meaning assessor and assessee solutions. The second phase identified changes in their discourse. For instance, choice of vocabulary, use of mediators, and a shift from ritual routines to routines of inquiry. In the third stage, each discourse paragraph was reread and changes in the discourse in the context of Sfard's (2012) theory were transcribed.

The findings presented focus on one group's on one group's entire process and analyzed in depth all the various stages of the discussion between the assessors concerning each and every solution. This choice served to demonstrate how the assessors succeed in assessing their peers despite their own difficulties in solving the assignment.

RESULTS

Sample Evaluation

Before giving a detailed analysis of the various data, the following example will illustrate how ideas and mathematical content were bounced between two assessors (S1 and S2) as they reviewed the solutions prepared by three assessees (E1, E2, and E3). While the classes under study had both male and female students, the interaction here is among female students, therefore the feminine pronoun has been used. The focus in this analysis is on the assessee's solutions to item (e) in the above problem involving exploration of a trigonometric function: Find the area of the figure constrained by *f(x)*, the above tangent, and x = -0.5.

Assessor solutions

First, let us examine S1's and S2's own solutions to the problem. S1 (see **Figure 3**) based her solution on calculating the area using a single integral and substituting $sin^2 x = t$. This is incorrect, the substitution does not lead her to solve the integral. So even though the rest of her calculations are correct, her final answer was not. S2 admitted that she did not know how to tackle the problem at all and thus presented no solution, which later led her to question how one can possibly assess something that one has no idea how to solve (line 24, below). However, as becomes apparent later, she did have some knowledge of how to go about it despite her feelings of ineptitude.

Defining criteria

S1 and S2 decided that a complete and correct solution of this section would include use of the integral and then a proper calculation of the area. They formulated two criteria for assessing the item: use of the integral for 60 points out of 100 and a proper calculation of the area for 40 points (they decided that a complete, correct answer for item (e) was worth 15% of the grade for the overall problem.)

Assessment of E1's solution

E1 tried to solve the integral by aiming to arrive at the form: $f(x) = \int [f^n(x) * f'(x)]\, dx$ (see **Figure 4**).

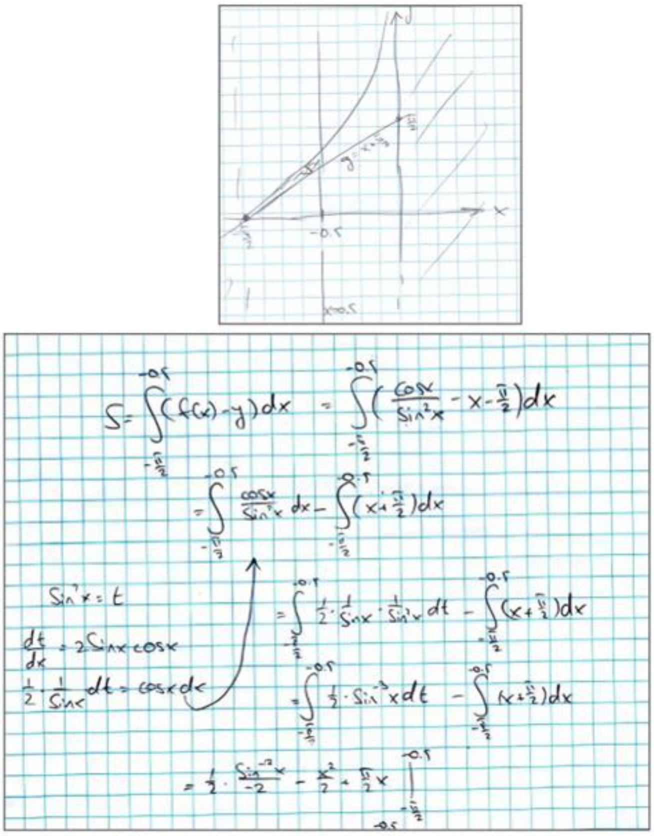

Figure 3. S1's solution (Source: Field study)

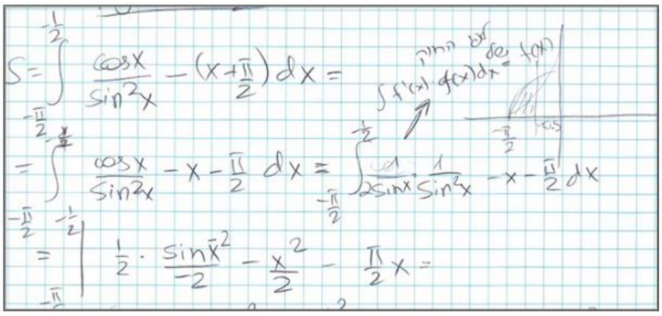

Figure 4. E1's solution (Source: Field study)

After a short inspection, S1 began to explain the content to S2, writing in her notebook to illustrate what she was trying to explain. Here is a segment of the dialogue between them (the actual dialog has been edited for clarity):

> 1. S1: She said $sin^2\, x\ = t$. Okay?
>
> 2. S2: Where? But she didn't substitute anything.
>
> 3. S1: No, wait a second. She took $sin^2\, x = t$, okay? That's what she said.
>
> 4. S2: Okay.
>
> 5. S1: And then she derived $dt = x$, right? Which is a 't' derivative, correct? It's $2\, sin\, x\, cos\, x$, okay? And then she multiplied and divided … and then you do an integral … then this, this is it, and then you can substitute them … She should have done an integral again, in my opinion. And then you get an integral of … and then you need to derive it according to … something like this. I myself also don't entirely know, this is what I did, this is also what she had done.
>
> 6. S2: She didn't do an integral, she just did something like a substitution.
>
> 7. S1: That's it. That's a substitution. It's what she needed to do.

Note that S1 is dominant and sometimes actually guides S2. However, her explanations are mainly driven by the question posed by S2. This sheds light on their sense-making processes. S1 explains E1's solution by substitution to S2. She points out that E1 did not use the substitute of the parameter "t," in contrast to herself. From the terms in the above dialogue – "She took … "; "She said … "; "She derived … " – I can see that S1 is trying to understand E1's solution process.

As the discussion progresses, it is apparent that while deciphering, S1 is constantly comparing E1's solution to her own work. As a result, she comes to the realization that something is missing in E1's solution. Indeed, her next sentence:

> 8. S1: She should have done, in my opinion, an additional integral … that's what I did, that's what she also did.

This leads her to immediately realize that something similar was missing in her own solution.

After this discussion, they decided to grade E1's solution with 50/60 for use of the integral and 40/40 for the calculations.

Assessment of E2's solution

Next, S1 and S2 reviewed E2's solution (**Figure 5**). E2 also chose to solve the problem using the substitution method and (in contrast to S1) calculated the integral correctly (E2's answer was the best and most correct of the five).

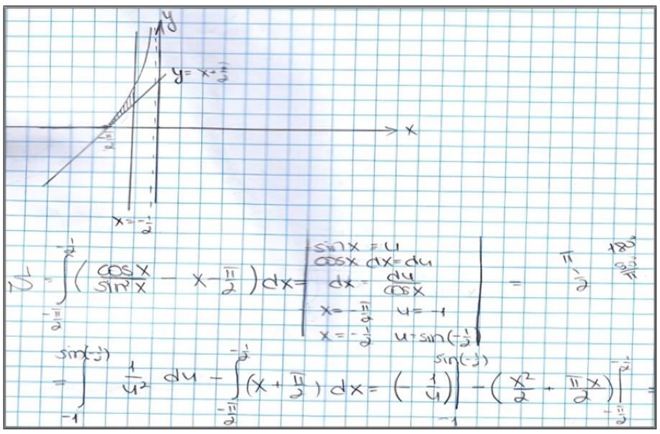

Figure 5. E2's solution (Source: Field study)

The following dialogue between S1 and S2 ensues. Note that S2 is now taking a more active role in the process than she did with E1's solution. She reads parts aloud, poses questions, and compares solutions.

> 9. S1: This is the integral itself. What did she do here?
>
> 10. S2: I don't know.
>
> 11. S1: Ha … [laughing] she did what????.
>
> 12. S1: She did a substitution.
>
> 13. S1: $-\sin x$ [hmmm] the $\sin x$ is u, then …
>
> 14. S1 & S2: $-cosx$ is.
>
> 15. S1: $\frac{du}{dx}$, and its derivative is $\cos x$, which is $-sinx$.
>
> 16. S2: But how did she get $dx = \frac{du}{\cos x}$? Why $cosx$?
>
> 17. S1: Because she derived $-sinx$ and then got $cosx$.
>
> 18. S2: Okay.
>
> 19. S1: Not $sinx$, not minus, and then $\cos x = \frac{du}{dx}$, and then $\frac{du}{\cos x}$ she substituted, and it came out like.
>
> 20. S2: Why did she do this [points to the limits of the integral] $sin -\frac{1}{2}$? Why sine in particular? Why between –1, what is –1? Where did it come from?
>
> 21. S1: She did here, in my opinion, according to the sine of these [points to the limits before the substitutions] $sin -90$ is $sin -\frac{1}{2}$.
>
> 22. S2: Ah … O.K.
>
> 23. S1: Ah … I understand, but it's still …
>
> 24. S2: How can we assess something which we don't know how to solve ourselves? It's a problem!

S1 and S2 start going over E2's solution from the same point of entry, that is, they both lack precise knowledge of how to solve the integral. In comparison to S1's quick initiative when explaining E1's solution, here she is cautious, and even starts the process with a question: "What did she do here?"

Here, too, S1 tries to decipher the solution, but she does not compare it (at least not overtly) to her own solution. S2's questions enable S1 to again play teacher and explain as required. However, despite the correct explanations, it appears that S1 is not completely sure of her answers: "She substituted, and it came out as … " (line 19); "She did here, in my opinion … " (line 21). This contrasts with her previous confident explanation of E1's solution.

At this stage, S2 appears frustrated with having to deal with E2's solution: Although S1 has correctly answered some of S2's questions, neither really understands how E2 solved the integral. From S2's utterance (line 24: "How can we assess something which we don't know how to solve ourselves? It's a problem!"), we can deduce that both feel they have reached an impasse.

The next step was to assign a grade. The dialogue below shows S1 and S2 trying to reach a decision about a suitable grade for E2's solution. They compare E1's and E2's solutions and both agree that E2's solution "looks more convincing."

> 25. S2: We'll give it full points; it looks good.
>
> 26. S1: Yes, the … I don't know, it looks to me …
>
> 27. S2: She got an answer, that's good already.
>
> 28. S1: Yes, I know. For the calculation she should get full points, because she knew what to do. But for the integral, I don't know, E1 [S1 pointing to E1's solution] also got 50. We gave her 50 out of 60.
>
> 29. S2: Yes, but E1 didn't do an integral at all and E2 did. E1 … as if she substituted what came out for her there in the substitutions.

Note that S2 is starting to take a more active role in the evaluation process as demonstrated by how she is taking a stand regarding which solution seems more correct.

After this dialogue, a few seconds of silence ensued. It seems that S1 was making an additional effort to understand E2's solution process. She is absorbed in silently reading the answer and suddenly succeeds in understanding the stages of the solution, as can be seen from the following explanation she gives S2:

> 30. S1: Look! … [raises her voice] She substituted the u as if it equals this [$sin\ x$], x equals $-\frac{1}{2}$ and then as if the square of u divided by du, she substituted here and the cosines, she substituted here as if $\frac{du}{dx}$. Instead of this, she factored, and then here she multiplied by $\frac{dx}{\cos x}$ and then it cancelled out …, and then it's $\frac{du}{u^2}$ and this she left as usual. Nice!

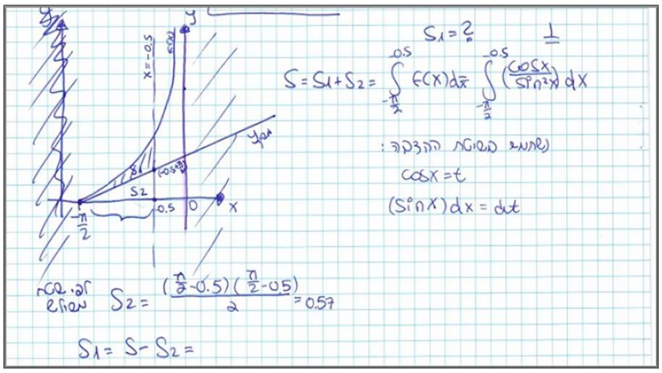

Figure 6. E3's solution (Source: Field study)

Assessment of E3's solution

After understanding E2's solution, S1 and S2 moved on to evaluate E3's solution (**Figure 6**). E3 divided the required area into two sections, one of which was a triangle. This approach was different than the others and a novel one for the assessors.

Below, we can see the discussion that took place between S1 and S2 concerning the grade that should be given to E3.

> 31. S1: Good, let's move on. Points for integral. [both start reviewing the item]. No. She didn't reach an integral at all.
>
> 32. S2: No, she didn't.
>
> 33. S1: But she did get the calculation and the method of solving the problem.
>
> 34. S2: Yes, she did substitute t and dt.
>
> 35. S1: Good. So for calculation and method she should get the entire 40 points. But she only started the integral, so how much will we give her? 20 out of 60?
>
> 36. S2: Wait! Why 40? What for?
>
> 37. S1: For the calculation and how she seemed to know it was necessary. Then she did all this, minus the triangle. [Reduction of areas to find the required area.]
>
> 38. S2: It seems she did an area of a triangle.
>
> 39. S1: E1 calculated the required area, and E2, named all this [pointing at the general area including the triangle].
>
> 40. S2: But why 40? She didn`t reach an answer. How did you get to 40?
>
> 41. S1: No, [she didn't get the final answer] but for the calculation and the way she knew what she needed to do.
>
> 42. S2: But there is no calculation.
>
> 43. S1: But the integral itself is this …
>
> 44. S2: Where do you see here a calculation?
>
> 45. S1: It's seemingly the way she chose to solve the problem.
>
> 46. S2: O.K., fine, let's say that [laughing].
>
> 47. S1: This is out of 20 points. 40% out of 20 is nothing.
>
> 48. S2: Okay.
>
> 49. S1: Okay. How many points should she get for the integral? She started something, let's say 20 out of 60?

It appears that S1 believes that the answer should receive a higher grade whereas S2 believes this is unwarranted because E3 did not calculate the integral, only the required area.

Notwithstanding their positions on the matter, the above dialog is interesting for two reasons. First, in contrast to the dialog regarding E1 in which S1 does most of the speaking and dominates the conversation, it shows that S2 no longer accepts everything S1 says. By this point, S2 has become an active partner and feels confident enough to state her position regarding the grade. Second, the terms used reflect S1 and S2's use of mathematical concepts thus giving them an opportunity to deepen their understanding of the topic.

Analysis of Learning Opportunities in the Example Given

A closer examination of the sample evaluation can shed further light on and afford deeper insight into the benefits of peer assessment as an instrument of learning. We noted that as S1 and S2 reviewed each solution, they were exposed to different solution methods and became aware of mistakes (both in their peers' and their own work), missing reasoning, unorganized documentation, etc. This exposure encouraged interactions during which the assessors divulged their opinions about the correctness or incorrectness of the assessed solutions, asked each other questions and attempted to answer them. All this comprises learning opportunities.

Using Harel and Koichu's (2010) terms of "disequilibrium" and "equilibrium" with respect to shifts from phases of not knowing to knowing was helpful in making sense of the data.

While S1 was explaining E1's solution to S2, she referred to her own solution method. This involved a series of mental acts including reading, deciphering, and assessing E1's solution; comparing it to her own; and explaining the solution to her partner. This illustrates a point when she was in a state of equilibrium. However, these led her to a stage where she realized that something was missing in the solution before: “She should have done, in my opinion, an additional integral” (line 8). To wit, this is the first example in which S1 is in a state of disequilibrium as she compares her work to E1’s throughout the assessment process. However, realizing what is missing in E1’s solution leads her to understand what is missing in her own.

In contrast to S1’s state of equilibrium when she had commenced to assess E1’s solution, she was in a state of disequilibrium when she began to assess E2’s solution. This is understandable considering the uncertainty she was experiencing concerning the question of how to solve the integral. The questions posed by S2 while reading the solution, and the answers given by S1, created alternating phases of equilibrium and disequilibrium.

Note too that during her attempt to understand E2’s solution, S2 indicated a state of surrender because she herself was not sure how to solve the problem. However, S1’s insistence on pursuing the analysis is an indication of her–as well as S2’s–level of involvement. S1 explained, very confidently, what she had understood. She then admitted that she had made a mistake in her own solution and thought aloud to understand where this mistake was and how to solve it correctly. The very context of both assessors working together triggered an incentive for S1 to try to understand, and she took on the teacher’s role.

DISCUSSION

In general, studying the video/audio data, the interviews, and written data (booklets and questionnaires) confirmed that peer evaluation offers many benefits to learning as it places students in a position where they have to make sense of their peers’ work. This often requires them to delve deeply into the solution process.

The data collected was revealing as to the actions students took to make sense of the assignment and to negotiate meaning. Specifically, students deciphered the solutions presented to them, compared these solutions with their own and with others reviewed previously, continually referred to the criteria, and interacted with their peers to discuss variations, nuances, meanings of the criteria, insights, ideas, impressions, and understandings. This also gave them the opportunity to discover mistakes in their own work and understand the importance of lucid writing and a high level of reasoning. All these have been promulgated by various researchers (Keaten & Richardson, 1993; Moschkovich, 1996, 1998; National Council of Teachers of Mathematics, 2009; Topping, 1998; Weaver & Cotrell, 1986) as critical to the learning of mathematics.

Data collected through the interviews and questionnaires suggests that the students themselves felt that this type of assignment offers opportunities for significant learning by showing them different ways of approaching a particular problem, possible mistakes that can occur, etc. The following are two excerpts from the interviews.

> The advantage here was to be able to see what other students had done. If I, let’s say, am taking an exam after seeing another solution, then, maybe it gives other options for solutions … Usually, this does not happen in class. It’s just solving exercises during lessons; it’s everyone to himself.

> I think it also helps when you can see your friends’ solutions. You see where they made such and such a mistake, and where they didn’t do something correctly, and then, from this, I get something for myself … I actually learn about what kind of mistakes can be made.

It also confirmed to them that they possessed more knowledge than they initially thought.

Analysis of the booklets revealed that this assignment helped foster better work habits when writing a solution. Some noted that they now appreciated the importance of order, organization, and a high level of detail when writing a solution and that their assessments were more stringent when the solutions their peers offered did not meet such standards.

A closer examination of the sample evaluation can provide deeper insight into the benefits of peer assessment as an instrument of learning. We noted that as S1 and S2 reviewed each solution, they were exposed to different solution methods and became aware of mistakes (both in their peers’ and their own work), missing reasoning, unorganized documentation, etc. This exposure encouraged interactions during which the assessors divulged their opinions about the correctness or incorrectness of the assessed solutions, asked each other questions and attempted to answer them. All this comprises learning opportunities.

The current study complements studies that base proof of learning solely on students’ self-reports and those that compare the marks allocated by peers to those given by the teacher (Strijbos & Sluijsmans, 2010). It identifies proof of learning by examining what students say, what they do, and how they reflect upon their experience.

The example presented involved pairing students who were heterogenous with respect to their (perceived) knowledge of mathematics. The exposure to E1’s solution led S1 to feel confident about the explanation she gave S2. The experience also gave her practice in analyzing another’s solution and understanding the other's steps in solving the problem. This sense of confidence emanates from the difference between the points of entry of the two assessors, according to which S1 thinks she had solved the problem correctly whereas S2 does not know how it should have been solved.

However, their exposure to both correct and incorrect solutions helped them realize where they had gone wrong in their own solutions and, eventually, how to correctly solve the problem.

In addition to the plethora of opportunities for involvement, I wish to point out that internal diversity, that is the different starting points of the assessors, also played an important role: it contributed to meaningful negotiations of meaning and thus enhanced peer teaching. In such situations, one evaluator might feel more comfortable than the other(s) in deciphering and assessing the solutions. This is fine, because the very act of verbalizing and making sense of the problem at hand is an opportunity for all to negotiate meanings and sharpen understanding.

From the point of view of the assessors, giving feedback to peers was valuable in that it demands deep understanding of the problem, the assessment criteria, and the relation between them. However, peer feedback was observed to be valuable to the assessees as well: I noted instances of meaningful learning within, and between, groups of assessors and assessees, collaborating Kollar and Fischer's (2010) claim.

Similar to Sluijsmans et al.'s (2000) and Zevenbergen's (2001) work in which students were partners in the stage of developing criteria, I also found that students also appreciated that taking a role in defining criteria offered critical learning because it forced them to clearly understand the mathematical concepts underlying the problem. Inter alia, they also saw it as a means by which they become partners with the teacher and the institution in coordinating expectations.

While the students expressed satisfaction with the exercise overall and reported that they felt it led them to better learning and understanding of the mathematical concepts, when asked whether the marks they assigned in this peer assessment activity should be integrated into the final mark for the course, they expressed that they did not feel comfortable with the notion of their assessments having any impact on their peers' final grades.

This echoes the findings in Wen and Tsai (2006) and Sambell and McDowell (1997) in which students were found to oppose such a move. As one student said:

> It's not objective. It's not as if you don't know the person. You know who it is from the outset, from the beginning. I'm sure that if you were grading a friend's test and you see that he made mistakes, you would say to yourself, What grade should I give him? I can't give him a low one. This is my friend. So, you will end up giving a higher score; maybe more than he deserves.

This presents a problem that Kollar and Fisher (2010) describe as "friendship marking" (p. 340). In order to avoid such a problem, Kollar and Fisher (2010) suggest combining peer assessment with co-assessment or self-assessment. Wen and Tsai contend that an anonymous evaluation may ease this reluctance and make the evaluation more reliable.

Taking into consideration the students' input and what we know from the literature, I decided from the onset not to include the marks obtained through the peer assessment activities in the final mark and to inform the students of this. I found this helped the students to be less anxious in using the whole scale of grades in assessing their peers.

It is worth noting that peer assessment contrasts to the traditional concept in which evaluation is solely in the hands of the teacher. Therefore, such practice as presented in this study might intimidate both teachers and students who are not accustomed to it (Kirkpatrick & Fuller, 1995).

CONCLUSION, IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH

In summary, there is considerable theoretical support for using peer assessment to promote student learning. Despite both the great potential and widespread use of peer assessment, empirical evidence regarding its effect on learning and the factors that might influence such effect is insufficient and inconsistent. In this meta-analysis, I found that peer assessment in general has a nontrivial positive effect on students' learning performance. This confirms previous literature on the benefits of peer assessment for student learning (Sanchez et al. 2017; Sebba et al., 2008; Topping, 2017). Furthermore, the impact of peer assessment is significantly greater when raters receive training and when assessment is computer-mediated rather than paper based. Although not statistically significant, a few other variables (such as rating format, rating criteria and frequency of peer assessment) also show some noticeable impact in explaining the variation of the peer assessment effect. The findings of this study can be used by researchers as a basis for further investigation and by teachers as a foundation for determining how best to use peer assessment as a learning tool. However, the process of peer assessment is complicated so that we cannot reliably code every aspect , and this is a primary limitation of this meta-analysis. For example, initially, I was interested in coding whether peer assessment is used for summative or formative purposes (Topping, 2017). However, information needed for coding that factor is not included in most studies and is difficult to infer. Also, student characteristics, such as native speaker/English-language learner and disability/no disability, are of great interest. However, usually the results are reported to all the participants instead of subgroups. Therefore, it was not possible to quantitatively examine these student characteristics. Further, our outcome measure is very general as I included a variety of tasks in the analysis. It would be an interesting research topic to distinguish between higher and lower order learning outcomes and to investigate how peer assessment as a treatment approach can impact those different learning outcomes. This study includes a limited number of more reliably coded variables to quantitatively describe the peer assessment process, and so some important qualitative differences may have been overlooked. Regarding future peer assessment studies, I would encourage researchers to provide further details about peer assessment procedures so that broader information can be made available to the field.

The current study reported on peer assessment tasks that were designed to promote focused interaction regarding mathematical concepts. The exercise led to an increased volume of peer interaction, personal responsibility, and positive inter-dependence (cf. Slavin, 1989). The nature of the tasks created learning situations in which students took on social roles (giving explanations, asking questions) together with learning roles (the need to learn about a correct solution and how to assess it correctly). These situations led to rich discussions and intensive listening while performing the stages of the task. It seems that the heterogeneous construction of the randomly chosen participants for each group invited confluence among different students who learned from each other, helped each other, and enriched each other's knowledge. All this took place in an environment in which learners could express their abilities and contribute their respective knowledge, understanding, and attitude (cf. Pain & Mowl, 1996). This study corroborates other studies that have suggested that social interaction in cooperative learning environments that exposes learners to a multiplicity of perspectives and a plethora of opportunities to exchange knowledge among group members can positively influence learners' achievements (Kollar & Fischer, 2010; Leikin & Zaslavsky, 1999).

Funding: No funding source is reported for this study.

Ethical statement: The author stated that the study was conducted in accordance with applicable ethical research standards, and that participants provided written informed consent after receiving an explanation of the study's objectives and procedures.

Declaration of interest: No conflict of interest is declared by the author.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the author.

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