Metacognitive Discourse Forums as a Way to Engage Biology and STEM Students in Meaningful Discussions

Dmitry Y. Brogun and Emral Devany

Kingsborough Community College of the City University of New York, USA

Dmitry.Brogun@kbcc.cuny.edu*, Emral.Devany@kbcc.cuny.edu

Abstract: The rapidly evolving educational landscape allows, and often demands, the integration of innovative digital approaches into the curriculum. Whether the course is conducted in-person, online, or hyflex, synchronous or asynchronous, the wide range of available digital tools and platforms now offer multi-faceted learning experiences designed to actively engage students. In our biology classes, we used Metacognitive Discourse Forum (MDF), an approach to collective annotation on an assignment, which may help students develop critical thinking, metacognitive skills, and improve academic performance. The article describes the utilization of MDF in our classes and discusses its potential impact for enhancing STEM teaching and learning.

Keywords: metacognition, discourse, Biology, STEM, social annotations

INTRODUCTION

Designed to improve metacognitive skills in STEM learning, Metacognitive Discourse Forums (MDF) is an andragogical approach that we used for interactive online discussions and student social annotations. It enables collective engagement with the course materials, which are visible to all peers and the instructor, fostering reflection and responses to other participants' contributions.

Metacognition involves the ability to reflect on one's thinking processes, and MDF provides space for students to engage in metacognitive practices (Pennequin et al., 2010; Alifiani et al., 2023). In MDF, students not only share their thoughts and ideas about their learning but also use annotations, which have been shown to strengthen students' critical thinking abilities (Johnson et al., 2010; Hwang et al., 2007). These discussions are not limited to text, but can also incorporate video content, offering an additional modality for learning. Students can ask questions, seek feedback from their peers and the instructor, and engage in discussions to improve their understanding of the course material. This approach helps students become aware of their learning

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processes, identify their strengths and weaknesses, and develop effective strategies for improving their learning experience.

In contrast to traditional discussion boards commonly built into learning management systems, such as Blackboard or Brightspace, where students are typically expected to read or view materials before reflecting on them, MDF offers the distinct advantage of capturing the “aha” moment. MDF enables students to comment in real time on the assignments or videos as they engage with them. As students view each other’s comments, the learning experience becomes more dynamic, collaborative, and interactive.

MDF can be implemented in a variety of ways to support student learning. They can support students' learning of specific content, help them develop critical thinking skills, or support their overall academic success. MDF can also promote a sense of a learning community and psychological safety for students (Fridman et al., 2025). The approach involves social annotations of readings and video content, followed by intra- and inter-group metacognitive discourse focused on the epistemology of the learner. This process enhances both subject-specific learning and the development of metacognitive awareness.

LITERATURE REVIEW

Academic research emphasizes that students are more likely to continue engaging in metacognitive activities in problem-solving when they understand their value and purpose; this is known as "informed" training, which is more effective than "blind" training (Lin, 2001; Brown et al., 1983). The term "metacognitive discourse forum" refers to structured conversations or reflections where individuals think and talk about their own thinking and learning processes. This kind of dialogue helps learners become more aware of how they learn, adjust, and develop better strategies. Dr. Burkart created an assignment that deliberately engaged students in metacognitive discourse by requiring them to reflect on and articulate: past learning struggles, reasons for focusing on specific topics, strategies they tried and learned, outcomes, and recommendations for others. This allowed students not just to do metacognition (thinking about their thinking), but to talk about it—hence, “metacognitive discourse.” It reinforced deeper learning by encouraging students to process and express their growth interactively (Burkart, 2022). Garrison and Akyol (2013) talk about the online discussion boards in online learning environments, wherein instructors have prompted students to engage in reflective forums where they must not only respond to content but also reflect on how their understanding evolved, what strategies they used, and what they found challenging. These forums promote both cognitive presence and metacognitive awareness.

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Metacognitive Discourse Forums, at their core, use reading and writing to represent a form of social interaction, serving as a dialogue between the author and the viewer/reader and the peers. Students can express this social aspect by annotating, which involves posting questions, leaving comments, cross-referencing external sources, and employing various other techniques to interact with text and video content. Social annotations, in turn, evolve, consolidating the annotations of a collective group. The advent of digital platforms has facilitated this process, enabling all students in a group to annotate shared content collaboratively. In STEM courses, we can tackle reading as a forum for communication that hinges on actively engaging with diverse perspectives to grasp the content fully. Social annotation serves as a channel for such communication, uniting the voices of all students in a group and promoting comprehension of the subject matter.

Previous studies showed the positive impact of social annotations. For example, Johnson et al. (2010) and Hwang et al. (2007) found that, compared to students who did not conduct social annotation activities, the students who conducted social annotation experienced improved metacognitive, critical thinking, and reading comprehension skills. Razon et al. (2011) compared 40 graduate students' comprehension and retention of course content using HyLighter, an online social annotation tool, and using paper highlights. They found that the students who used HyLighter better understood the course content than those who annotated on paper. Gao (2013) found that, out of a group of 122 undergraduate pre-service student teachers, the majority of the students left more comments during an annotation activity than they had to, and that the majority reported having a positive experience using the social annotation activity to learn their course content.

Aguillon and Monterola (2020) examined the influence of Web 2.0 technology, specifically online collaborative video annotation (OCVA), on the reflective thinking and academic self-discipline of STEM students. Their investigation revealed that while OCVA did not significantly impact overall reflective thinking, it influenced the component of understanding in the reflective thinking process. Moreover, this innovative learning approach positively affected habitual action and academic self-discipline, specifically among low-performing students in STEM and in General Chemistry 1. These studies underscore the intricate relationship between technology-enhanced learning and metacognitive processes, signifying how students engage with and benefit from multimedia resources in the contemporary educational landscape.

Tanner emphasizes integrating metacognition into undergraduate biology education to help students think like biologists and further suggests explicit teaching of metacognitive strategies, creating a classroom culture that encourages reflection and sharing of confusion, and modeling metacognition by instructors. Examples include prompting students to ask self-questions about their learning process, integrating reflection into assignments, and demonstrating problem-solving approaches (Tanner, 2012).

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In learning activities, metacognition can be assessed through targeted instruction that prompts students to reflect on their cognitive processes (Lai, 2011). Metacognitive interventions serve as practical tools in activating these processes. One such intervention involves using metacognitive questions, segmented into categories including comprehension, connection, strategic, and reflection questions (Özcan & Erktin, 2015). As Faradiba et al. (2019) highlighted, comprehension questions facilitate students' grasp of concepts, while connection questions encourage them to establish links between the current topic and previously encountered concepts. Strategic questions aid students in determining the most efficient approach to address biological inquiries or challenges. Lastly, reflection questions prompt students to assess the methodologies employed in addressing questions and evaluating their responses (Alifiani et al., 2023).

METHODS

In this study, we used a qualitative approach to explore how the Metacognitive Discourse Forums were used to assist students in solving population genetics problems in General Biology II at Kingsborough Community College, Brooklyn, The City University of New York. This research falls under exploratory descriptive categorization. It aims at determining the outcomes of using metacognitive discourse forums with students solving Population Genetics problems in Biology. The data was primarily collected through the Metacognitive Discourse Forums conducted with students, while they solved population genetics problems to determine the allele frequencies by applying the Hardy-Weinberg Theorem.

The investigation commenced with a cohort of 37 students enrolled in General Biology II. The instructional sessions spanned over three meetings, during which all student activities and interactions were observed and documented. The methodology and educational interventions applied throughout these sessions are detailed in Table 2. The number and structure of these sessions can be modified according to the modality of the class. In this class, students were encouraged to complete MDF before attempting to solve the population genetics problems assigned. Although using MDF was strongly encouraged, it was not mandatory.

The framework of metacognitive questions utilized during the MDFs and the follow-up in-person meetings, which facilitated the metacognitive intervention, is outlined in Table 1.

Types of Metacognitive Questions	**Metacognitive Questions**
Comprehension Question	1)What is the material related to this problem? 2) Can you show the allele frequencies that you are looking for?

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Connection Question	1) Did you immediately solve this problem in the same way as you did before? 2) What are the differences between this question and the questions you have done before? 3)Have you ever worked on questions like this before?
Strategic Question	1) What strategies can be used to solve the problem? 2) Why is this considered the right strategy? 3) What is the Hardy-Weinberg Theorem?
Reflection Question	1) Is the process correct? 2) Does the solution make sense? 3) Is there any other way to solve this problem? 4) What did you find confusing?

Table 1: The Metacognitive Questions. Inspired by (Tanner, 2012).

Meeting 1	**Meeting 2**	**Meeting 3**
Objective: Topic introduction, assess students prior knowledge on the topic. Provide instructions to students on the MDF completion, covering the What, When and How questions. Activity: In-person Laboratory lecture-discussion on Population genetics, Allele Frequencies and Hardy-Weinberg Principle, Theorem, Equilibrium, and Conditions. For homework, students were asked to participate in the MDF and solve four Population genetics problems to determine the Allele frequencies by applying the Hardy-Weinberg Theorem.	Objective: Instructor-led student engagement in MDF. Students show their understanding, critical thinking and reflection by asking and answering self, peer and instructor questions. Activity: Asynchronous online MDF on Hardy-Weinberg Principle, Theorem, Equilibrium, and Conditions. Solving the four population genetics problems.	Objective: Cover student misconceptions and verbal assessment of student's metacognitive skills. Activity: In-person laboratory lecture-discussion on the results and the solutions of the four Population Genetics problems and determining the allele frequencies using the Hardy-Weinberg Principle, Theorem, Equilibrium, and Conditions.

Table 2. Sequence of the Learning Activities.

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The Lesson: Solving a Population Genetic Problem by the Hardy-Weinberg Theorem.

Direct evidence of an evolving population is a change in allele frequencies. The Hardy-Weinberg Theorem is one way to determine whether allele or genotype frequencies are changing from generation to generation. It states that alleles and genotype frequencies do not change from generation to generation under the following conditions. Most conditions (assumptions) are unmet in natural populations, so populations evolve (Brogun et al., 2021).

Changes in allele frequencies can be calculated based on the following equations:

$$p + q = 1 \tag{1}$$

p = frequency of dominant alleles in a population
q = frequency of recessive alleles in a population

Squaring both sides

$$(p + q)^2 = 1^2 \tag{2}$$

will yield:

$$p^2 + 2pq + q^2 = 1 \tag{3}$$

p^2 = frequency of homozygous dominant genotypes (individuals) in a population
q^2 = frequency of homozygous recessive genotypes (individuals) in a population
$2pq$ = frequency of heterozygous genotypes (individuals) in a population

The conditions (assumptions) of the Hardy-Weinberg Equilibrium include: No mutations, random mating, no natural selection, extremely large population size, no gene flow, and no genetic drift.

Creating the Assignment That Incorporates Metacognitive Discourse Forums:

We created video lessons in Dropbox, embedded the videos in the Learning Management System, i.e. Blackboard or Brightspace, and assigned students to view the videos and make annotations in the LMS. Below is a description of how we implemented the Metacognitive Discourse Forum.

To set up the MDF, begin by creating a video that introduces the assigned reading materials and covers the critical points for the MDF. The video should include a voice-over narration summa-

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rizing the content, highlighting key concepts, and identifying critical points for discussion. Screen recording or video editing tools may be used to combine the narration with relevant slides or text excerpts to enhance clarity and engagement. Once complete, upload the video to a clearly labeled folder in Dropbox (e.g., "Metacognitive Discourse Forum Materials – [Date/Topic]").

Next, generate a shareable link to the video and copy the link. In the LMS, navigate to the appropriate course, create a new content item or module, and embed the Dropbox video link using the content editor. Ensure the video opens properly for students. Configure the link as a Content Provider, which will create a gradebook column to track participation.

It is important to include detailed instructions clearly outlining student expectations, such as the required number of annotations, peer replies, and instructor interactions needed for full credit. Sample student instructions are provided below:

1. Accessing the Forum:
   - Go to the Metacognitive Discourse Forum section in your LMS.
   - Click on the provided link to access the video recording.
2. Making Annotations:
   - While watching the video, make annotations and answer questions posted by the instructor.
   - Review the assigned reading materials and make annotations directly in the Metacognitive Discourse Forum within the LMS. You are required to make a minimum of [X] annotations on key points, answer questions, and raise questions related to the video or a reading.
   - Ensure your annotations are thoughtful and contribute to the discussion. Highlight important concepts and provide your perspective.
3. Responding to Peers:
   - Read and review annotations made by your peers. You are required to reply to at least [Y] peer annotations. Your replies should be constructive, engage with the content, and further the discussion.
   - When replying, provide thoughtful comments revealing your critical thinking, ask clarifying questions, or offer alternative perspectives.
4. Receiving Instructor Feedback:
   - Monitor the forum for responses from the instructor. The instructor will provide feedback on your annotations and participation.
   - Replies from the instructor will be available in the forum and may also be reflected in the gradebook column created through the Content Provider setup.
5. Grading and Feedback:
   - Points for annotations and peer interactions will be recorded in the LMS's gradebook, visible under the grading column.

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- Ensure you meet all requirements for annotations and replies to receive full credit.

To make the most of the Metacognitive Discourse Forums, participants should regularly check the forum for updates and feedback, ensuring they stay informed and responsive. Active engagement is key; students are encouraged to contribute thoughtfully to discussions and respond meaningfully to their peers. By following these guidelines, both instructors and students can use the forums effectively to deepen their engagement with course materials and enhance overall learning.

RESULTS

In this study, the Metacognitive Discourse Forum was used to engage students in class content in a meaningful way. Students were presented with content in the form of video and text. Students were asked metacognitive questions that addressed the higher order of Bloom's taxonomy, including comprehension, strategy, connection, and reflection (Table 1), and were assigned to use social annotation tools. Figure 1 depicts examples of the student responses in MDF using the Dropbox platform with student-content, student-student, and student-instructor social annotations of the Instructor-narrated video of the assigned reading. Figure 1 includes screenshots from actual student responses. Figures 1a and b demonstrate a comprehension question (see Table 1) asked by the instructor, prompting students to think about the significance of the Hardy-Weinberg principle as it relates to evolution. Students paused the reading and video to think about what they were learning, and students' reflections are shown (Figures 1a and 1b). Likewise, in another example, students were asked a reflection question (Figure 1c and see Table 1). Students were asked to reflect on what they found most confusing in the Hardy-Weinberg Theorem. As seen in Figure 1c, most students found the allele frequency calculations confusing.

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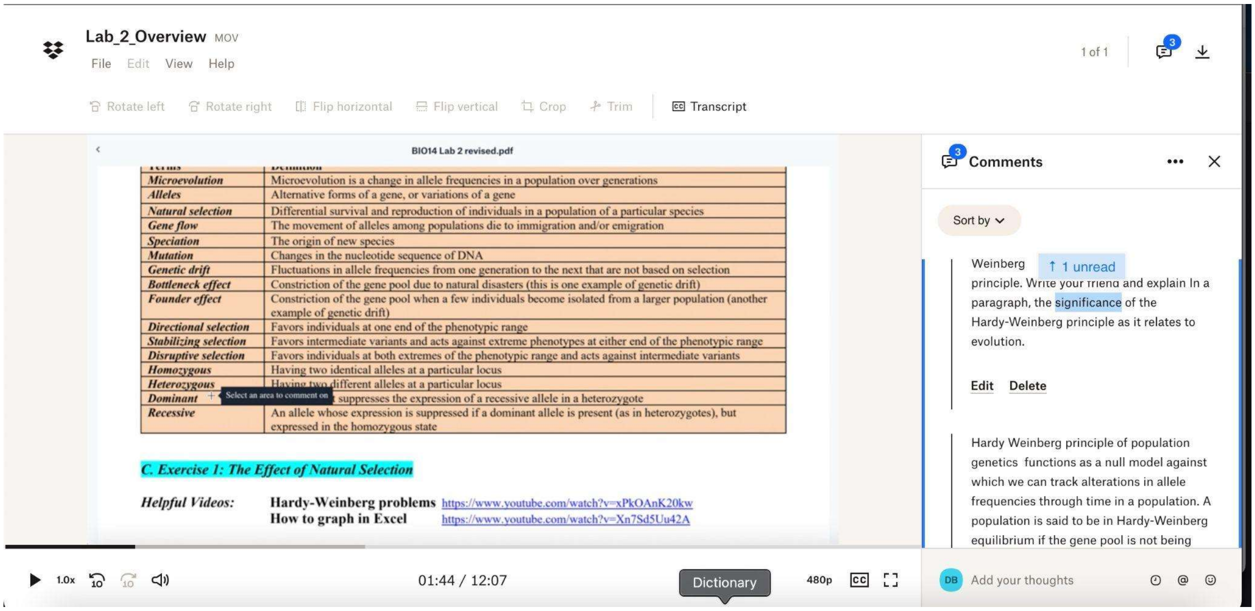

Figure 1a: Example of the student responses to MDF's Connection and Reflection questions (see Table 1).

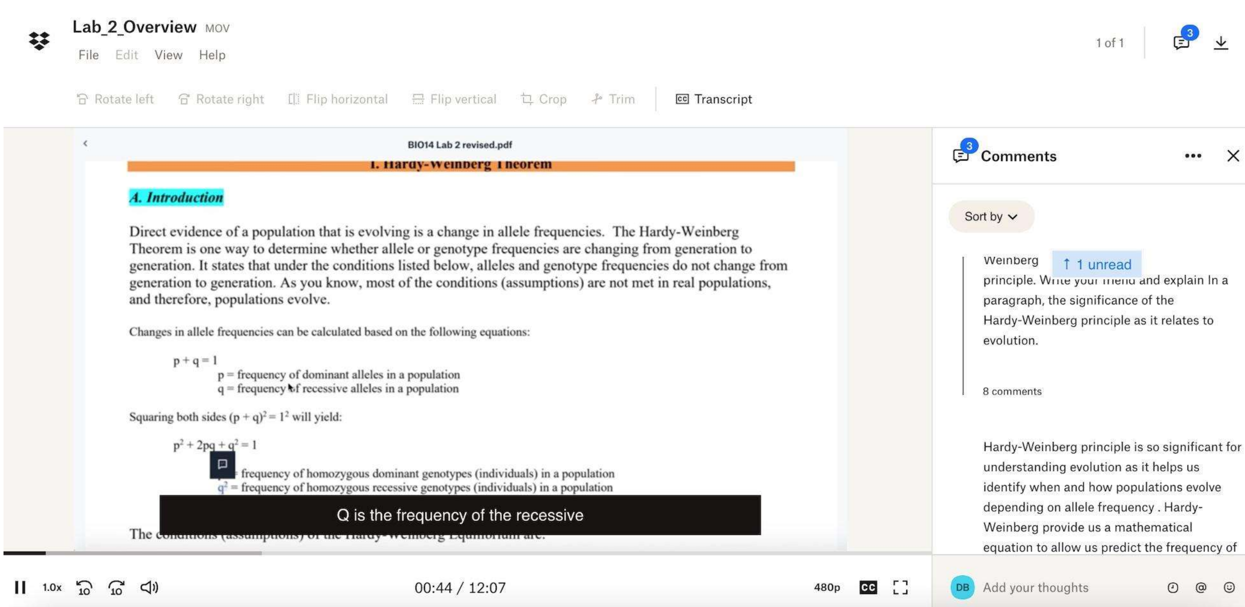

Figure 1b. Example of the student responses to the Strategic Questions in MDF (see Table 1).

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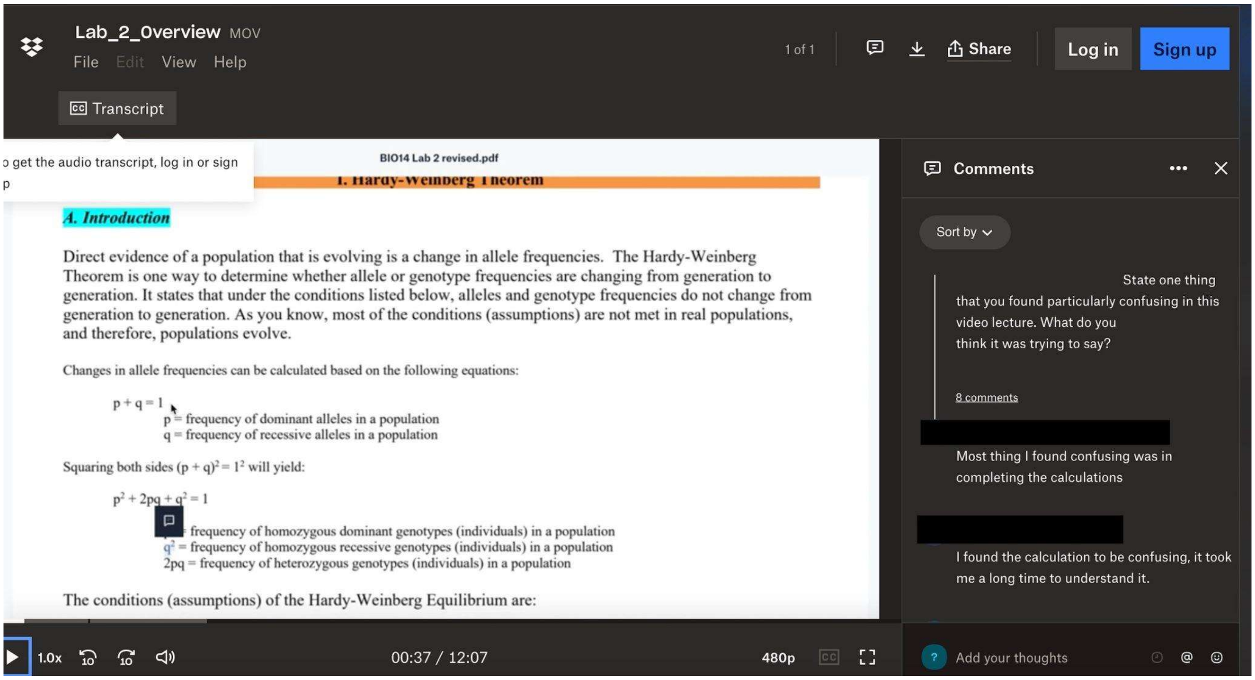

Figure 1c: Example of the student responses to Reflective Questions regarding confusion in MDF (see Table 1). Student names are blocked for viewing.

Students were asked to solve four population genetics problems to determine allele frequencies and then show calculations and the answers in their Lab Journals. Problem 1 asked them about a population of 16 pigs where the allele for a gray coat is recessive. Use the Hardy-Weinberg equation to determine the percentage of the pig population heterozygous for pink coats. Four gray coats and 12 pink coat pigs are in the population—a possible solution to Problem 1. The Hardy-Weinberg Theorem states that allele frequencies will remain constant from generation to generation if there is no selection, mutation, migration, or genetic drift in a population where mating is random.

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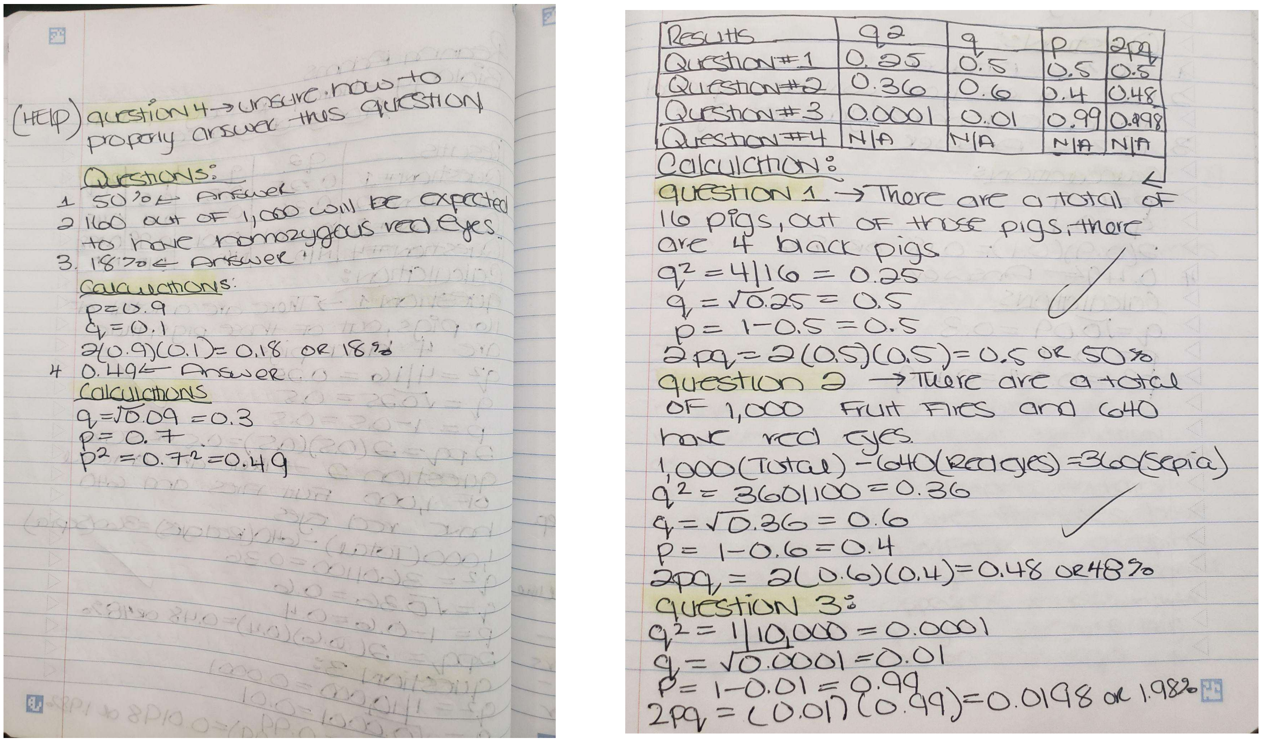
(HELP) question 4 → unsure how to properly answer this question

Questions:

1 50% ← Answer
2 160 out of 1,000 will be expected to have homozygous red eyes.
3. 18% ← Answer

Calculations:
p=0.9
q=0.1
2(0.9)(0.1)=0.18 or 18%

4 0.49 ← Answer

Calculations
q=√0.09 =0.3
p=0.7
p²=0.7²=0.49

Results	q2	q	p	2pq
Question#1	0.25	0.5	0.5	0.5
Question#2	0.36	0.6	0.4	0.48
Question#3	0.0001	0.01	0.99	0.198
Question#4	N/A	N/A	N/A	N/A

Calculation:
Question 1 → There are a total of 16 pigs, out of those pigs, there are 4 black pigs
q² = 4/16 = 0.25
q = √0.25 = 0.5
p = 1-0.5 = 0.5
2pq = 2(0.5)(0.5) = 0.5 or 50%
Question 2 → There are a total of 1,000 Fruit Flies and 640 have red eyes.
1,000(Total) - 640(Red eyes) = 360(Sepia)
q² = 360/100 = 0.36
q = √0.36 = 0.6
p = 1-0.6 = 0.4
2pq = 2(0.6)(0.4) = 0.48 or 48%
Question 3:
q² = 1/10,000 = 0.0001
q = √0.0001 = 0.01
p = 1-0.01 = 0.99
2pq = (0.01)(0.99) = 0.0198 or 1.98%

Figure 2a: Student answers to the Population Genetics problems 1 through 4 who participated in MDF. On the left, the student's initial response to the problems. On the right, students' improved responses based on interaction with the instructor and peers via MDF.

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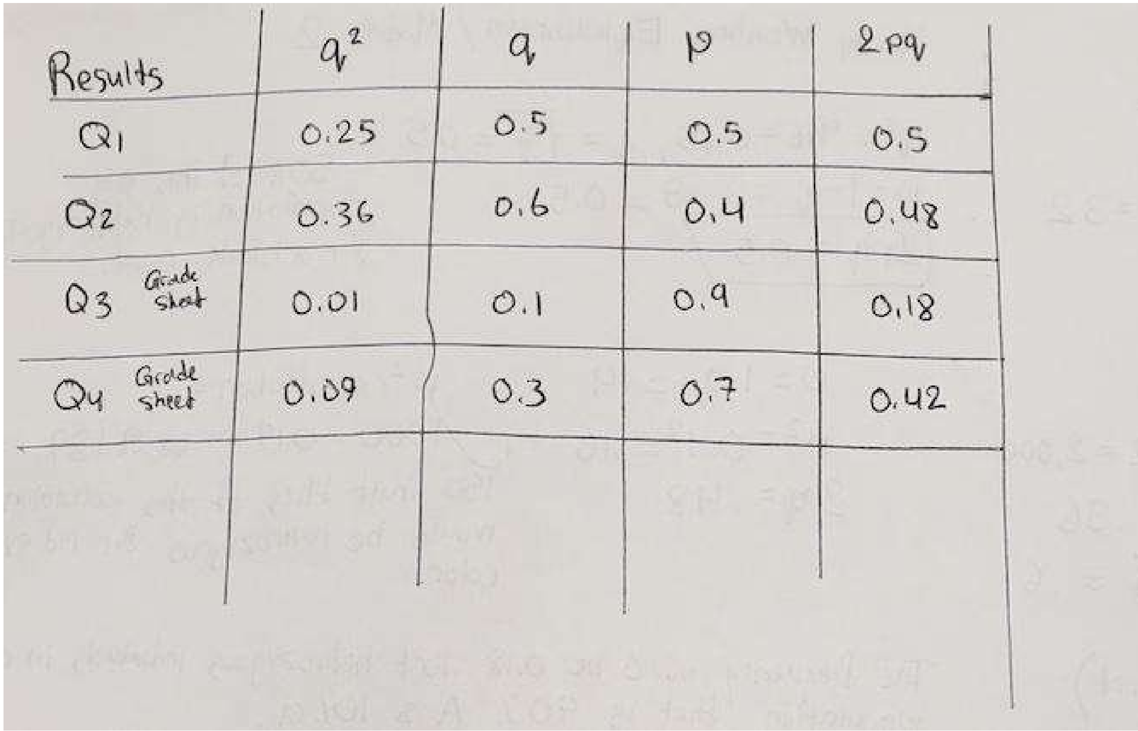

Results	q^2	q	p	$2pq$
Q1	0.25	0.5	0.5	0.5
Q2	0.36	0.6	0.4	0.48
Q3 Grade sheet	0.01	0.1	0.9	0.18
Q4 Grade sheet	0.09	0.3	0.7	0.42

Figure 2b. Student answers to the Population Genetics problems 1 through 4 who did not participate in MDF.

For the Hardy-Weinberg Theorem and calculations, please see the methods section. As described in the methods section, completing MDF was strongly encouraged but optional. Two student examples are shown in Figure 2 as a representation of submissions from students who completed the MDF before attempting homework problems (2a) and students who did not complete the MDF (2b). Students who completed MDF showed their calculations and provided answers to the population genetics problems. When these students encountered confusion, they communicated these concerns to the instructor. Figure 2a shows a student's response before and after interacting with their instructor and peers. After the MDF intervention, the student was able to reflect and explain their understanding.

Furthermore, the instructor was able to assess what the students learned and what they were still lacking. In this example, this student was still having difficulty with question 4. Hence, this intervention also provides feedback to the instructor on what students are still struggling with and what could be addressed during meeting 3 (see Table 2). Conversely, students who did not engage with the MDF omitted their calculations in their submissions. While some of these answers were correct and others incorrect, there was no evidence for the instructor to assess the student's learning process or understanding.

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Of the 37 students in this study, 17 engaged in the MDF annotations and successfully demonstrated their calculations for the four population genetics problems. However, three students made calculation errors in this group, leading to incorrect answers. Despite these initial mistakes, their underlying logic and calculation processes were clear and indicative of a correct conceptual understanding, but faulty execution. Remarkably, after participating in the in-person third session meeting, these students could self-identify and correct their calculation errors, showcasing an example of metacognition. This ability to reflect on and adjust their learning process highlights the significance of metacognitive strategies in academic success.

In contrast, only seven out of the 20 students who did not participate in the MDF managed to provide correct answers to the problems. We observed that all 20 students who bypassed the MDF engagement needed help articulating their problem-solving process or explaining how they arrived at their solutions to the four population genetics problems. This lack of self-awareness and inability to reflect on their thought processes underscores the essential role of metacognition in not just achieving correct outcomes but in developing a deeper, articulated understanding of the material. Engaging with MDF not only facilitates correct problem-solving but also potentially enhances students' metacognitive abilities, allowing them to better understand their learning processes.

Our findings demonstrated the potential effectiveness of MDF in improving students’ metacognition, building connections among students and between students and instructors, and supporting students’ learning in general. Here we demonstrate with examples how MDF helped students to pause and think about their learning and ask for help when they needed it.

DISCUSSION

STEM instructors look for ways to support students’ learning and success in their field. Different approaches are used to achieve this; instructors look for ways to improve students’ critical thinking, engagement, and metacognition. They also aim to provide a supportive classroom environment where students and instructors can interact freely and comfortably and find ways to quickly and effectively assess student learning. Although different tools and methods have been used, here we describe MDF as a tool that provides a space to achieve these goals all at once. In this study, we explored MDF to engage all students in class content via video and text format simultaneously and to pose metacognitive questions (see Table 1 for examples) to prompt students to monitor and evaluate their learning. In addition to presenting class materials and metacognition, MDF included social annotation. This type of metacognitive reflection helps students evaluate their own learning, and social annotation helps students to express their thinking, connect with their peers and their instructor, and ensure that the instructor can get instant feedback. The instructor then knows what to address during the class discussion.

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An example of a potentially beneficial use of MDF is shown in this study. After an in-person discussion on population genetics, allele frequencies, and the Hardy-Weinberg Theorem (see Table 2), students were encouraged to participate in MDF and were assigned to solve four population genetics problems to determine the allele frequencies. Here, we used Dropbox as an MDF platform. To show their thinking and learning, students were asked metacognitive questions. The students who completed the MDF and actively participated in social annotation were able to show their thinking and work for solving the problems. They were able to evaluate their learning, identify their confusions, and ask for help from the instructor. They were also able to connect with their peers. For example, when the instructor asked about the most confusing part of this topic, most of the students identified calculations as the most challenging aspect (Figure 1c). This provides a support environment in class and instantly provides feedback to the instructor. On the other hand, students who did not complete the MDF could not express their thoughts. Although they may have given answers to the problems assigned, they demonstrated suspension of sense-making, not being able to express their thinking, the ways they solved the problems, or identify their confusions. Since these students did not complete the MDF and/or show any work in their assignment, the instructor cannot monitor students' learning or address confusion.

Our study supports previous literature and adds another dimension to support student learning. The positive impact of social annotation in text (Johnson et al., 2010; Hwang et al., 2007) and video (Aguillon and Monterola, 2020) formats has been demonstrated. Here, we use MDF to simultaneously incorporate social annotation in text and video formats. Integrating metacognition into STEM, and especially biology education, was shown to help students think like biologists (Tanner, 2012). Furthermore, targeted instruction effectively promoted metacognition (Lai, 2011). In this study, MDF showed a potential to be a platform where targeted instruction through metacognitive questions improved students' thinking and learning.

Instructors who are interested in using MDFs in the classroom should keep a few aspects in mind. First, they need to choose a forum platform appropriate for their students' needs. There are several different platforms available, so instructors can select one that is easy to use and that will allow tracking student participation. Second, the instructor must create a clear and concise learning objective for the MDF (see Table 2). Once the instructor has clear objectives, they can design activities and discussions that will help students achieve those objectives. Third, instructors need to guide students on how to participate in the MDF. This includes demonstrating how to use the forum platform, post thoughtful and constructive comments, and respond to the comments of others (Figure 1). Finally, instructors need to monitor the MDF and provide constructive feedback to students. This will help to ensure that students are using the forum effectively and that they are getting the most out of their participation. MDF can be a valuable tool for supporting student learning in biology and STEM. MDF may be a good option for the instructors who are looking for a way to help their students develop metacognitive skills, improve critical thinking skills, and increase academic achievement.

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CONCLUSIONS

The study utilized Metacognitive Discourse Forums to address problem-solving challenges as part of the metacognitive intervention. These forums provided a platform for STEM students to engage in reflective dialogue, address cognitive gaps, and receive feedback on their problem-solving processes. Metacognitive support, including discussions in these forums, helped biology students move from procedural to more integrated conceptual understanding.

Educators should consider integrating Metacognitive Discourse Forums into their teaching and learning practices to promote deeper cognitive engagement and enhance learning flexibility. By incorporating these forums, educators can support a reflective, inclusive, and interactive learning environment where students engage in discussions that promote self-awareness, psychological safety, and critical thinking about their learning processes. This can be achieved by providing additional guidance for learners engaged in Metacognitive Discourse Forums by scaffolding support and encouraging self-regulation and metacognitive reflection.

Educators should regularly monitor student progress, offer timely feedback, and adjust teaching strategies based on feedback gained from Metacognitive Discourse Forums. This approach allows for real-time adjustments to improve learning outcomes. Above all, educators should implement a combination of formative and summative assessments that are validated through rubrics and closely aligned with learning objectives. Use feedback from Metacognitive Discourse Forums to ensure assessments are fair and effective. By incorporating the Metacognitive Discourse Forums to facilitate reflective learning and problem-solving, instructors can improve the learning experience by ensuring user-friendly interfaces, such as using Dropbox, providing clear instructions, and making technical support readily available.

By implementing these recommendations, educators can ensure flexible teaching and learning using Metacognitive Discourse Forums, especially in STEM education. Educators should continuously evaluate and refine their action plans based on feedback and evolving needs, ensuring a sustainable and impactful approach to teaching and learning.

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About the Authors

Dmitry Y. Brogun has been educating students in Biological Sciences at CUNY since 2007. At Kingsborough Community College, CUNY, he has served as a Metagenomics Discovery Challenge PI and as a mentor for the CUNY Research Scholars Program (CRSP), Bridges/CSTEP (Bridge to Bachelor's Program at Medgar Evers College/Collegiate Science Technology Entry Program), and as a Science Coordinator for STEP (Science Technology Entry Program). Along with his Kingsborough colleagues, he has published an OER Biology Laboratory Manual. His primary educational focus has been on elevating students' skills in scientific inquiry, and he also has an interest in andragogical studies in STEM to determine the best classroom/lab practice.

Emral Devany is a Professor of Biology at Kingsborough Community College, CUNY, with a Ph.D. in Biochemistry from Hunter College. Her research focuses on mRNA processing, gene regulation, and innovative STEM teaching methods. As a leader in curriculum innovation, she integrates writing-intensive instruction, learning communities, and OER into courses like General Biology and Anatomy and Physiology. Dr. Devany is active in faculty development through her work with the Faculty Initiative on the Teaching of Reading and leads cross-campus initiatives to promote inclusive, evidence-based STEM education.

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