Collaborative Creativity in Proving: Adapting a Measurement Tool for Group Use

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Creativity is central to mathematics and mathematics education. One hindrance to research in mathematical creativity is the complex nature of defining and measuring creativity. Some efforts have been made to study mathematical creativity at the K-12 level, but just recently researchers have begun exploring mathematical creativity at the undergraduate level. Proof is essential to an undergraduate mathematics education, and as university mathematics classrooms evolve to incorporate more active and collaborative learning, it is imperative to understand the relationship between collaboration and creativity in proving. This study seeks to apply the Creativity-In-Progress Rubric (CPR) on Proving (Savic et al., 2017) to two collaborative small-group proving episodes and to evaluate its ability to present a holistic image of a group's creative proving process. Findings of this evaluation led to the three suggestions for future use of the CPR on Proving in collaborative settings.

Keywords: mathematical creativity, proof, creativity in proving, collaboration

Creativity is a central tenant of mathematics, and mathematical creativity is a rapidly growing research area. Between the years 2000 and 2021, there are over 6000 items on Google Scholar that contain the phrase "mathematical creativity," and about 1300 of these were published in the years 2019 or 2020. Mathematical creativity has been recognized as an important part of mathematics education. Neglecting mathematical creativity in mathematics curricula denies students from truly understanding what mathematics is and from seeing the beauty of mathematics (Mann, 2006), and encouraging students to think creatively is essential to successful mathematics major courses (Schumacher & Seigel, 2015).

This study investigates the assessment of collaborative creativity in proving. I seek to answer the question: how can creativity in proving be assessed in a collaborative setting? I wish to examine the ability of the existing individual Creativity-In-Progress Rubric (CPR) on Proving (Savic et al., 2017) to depict a holistic representation of the creative process of a group. This study's theoretical framework aligns with that of Savic et al. (2017); I assume that mathematical creativity is domain specific, relative in terms of context and background, and assessed as a process rather than a product.

Background Literature

Defining mathematical creativity has been a difficult task for scholars in mathematics and mathematics education (Karakok et al., 2015; Mann, 2005, 2006; Nadjafikhah et al., 2012; Sriraman, 2004). Definitions of creativity vary depending on whether creativity is characterized as: domain-general or domain-specific, a process or an end product, and relative or absolute (Savic et al., 2017). Lack of a central definition of mathematical creativity has created a challenge in measuring creativity and thus pursuing research in mathematical creativity.

Despite difficulties in defining creativity, there have been several attempts to create a measure of both domain-specific and domain-general creativity (e.g., Kattou et al., 2013, Leikin & Elgraby, 2020; Levav-Waynberg & Leikin, 2012; Savic et al., 2017; Siswono, 2010; Torrance, 1966, 1974). Guilford's (1959) characterization of creativity aimed to present testable factors of creativity and has been commonly used as a framework for measuring and defining creativity.

The four aspects of creativity, as suggested by Guilford, are fluency, flexibility, originality, and elaboration. This characterization inspired the Torrance Tests of Creative Thinking (TTCT; Torrance, 1966, 1974) to measure domain-general creativity, the similar Mathematical Creativity Test (MCT; Kattou et al., 2013) to measure domain-specific mathematical creativity, and many others (e.g., Leikin & Elgraby, 2020; Levav-Waynberg & Leikin, 2012; Siswono, 2010).

The Creativity-In-Progress Rubric on Proving

MAKING CONNECTIONS:	**Beginning**	**Developing**	**Advancing**
Between Definitions/Theorems	Recognizes some relevant definitions/theorems from the course or textbook with no attempts to connect them in their proving	Recognizes some relevant definitions/theorems from the course and attempts to connect them in their proving	Implements relevant definitions/theorems from the course and/or other resources outside the course in their proving
Between Representations[1]	Provides a representation with no attempts to connect it to another representation	Provides multiple representations and recognizes connections between representations	Provides multiple representations and uses connections between different representations
Between Examples	Generates one or two specific examples with no attempt to connect them	Generates one or two specific examples and recognizes a connection between them	Generates several specific examples and uses the key idea synthesized from their generation
TAKING RISKS:	**Beginning**	**Developing**	**Advancing**
Tools and Tricks	Uses a tool or trick that is algorithmic or conventional for the course or the student	Uses a tool or trick that is model-based or partly unconventional for the course or the student	Creates a tool or trick that is unconventional for the course or the student
Flexibility	Attempts one proof technique	Acknowledges the possibility of different proving approaches, but attempts no further examination	Acts on different proving approaches
Perseverance	Begins to engage with proving	Continues to engage with surface level features but not with the key ideas	Continues to engage with the key ideas
Posing Questions	Recognizes a question should be asked, but does not formulate a question	Poses questions clarifying a statement of a definition or theorem	Poses questions about reasoning within a proof
Evaluation of the Proof Attempt	Checks work locally	Recognizes a successful or unsuccessful proving attempt	Recognizes the key idea that makes the proving attempt successful or unsuccessful

[1] We define a *mathematical representation* similar to NCTM's (2000) definition. It includes written work in the form of diagrams, graphical displays, and symbolic expressions. We also include linguistic expressions as a form of lexical or oral representation. For example, a student can use the lexical or oral representation, "the intersection of sets A and B"; a Venn Diagram to depict his/her mathematical thinking; a symbolic representation $A \cap B$; or set notation $\{x | x \in A \text{ and } x \in B\}$ (which is also a symbolic representation). Note the last two representations are in the same category, e.g. symbolic, but they are still considered two different representations.

Figure 1. The Creativity-In-Progress Rubric. From "Formative Assessment of Creativity in Undergraduate Mathematics: Using a Creativity-in Progress Rubric (CPR) on Proving" by Savic M., Karakok G., Tang G., El Turkey H., Naccarato E., 2017 In R. Leikin & B. Sriraman. (Eds) Creativity and giftedness (pp. 23–46). https://doi.org/10.1007/978-3-319-38840-3. *Copyright 2017 by Springer International Publishing.*

The CPR on Proving, which can be seen in Figure 1, assumes creativity to be domain-specific, a process, and relative. The most recent published version of the CPR on proving (Savic et al., 2017) presents two categories: making connections and taking risks, which are split into subcategories. Student work is assessed on a continuum to characterize the proving process of an individual student. The CPR on proving has been used as both a formative assessment tool (e.g., El Turkey et al., 2018) and a student reflection tool (e.g., Omar et al., 2019; Tang et al., 2017). The Creativity Research Group (Creativity Research Group, 2020) has suggested future research on the influence of socialization and collaboration on creativity in proof (Savic, 2016) using the Creativity-In-Progress Rubric.

Group Creativity

The Creativity-in-Progress Rubric on Proving was designed to measure the creative efforts of an individual student, yet students in a classroom do not necessarily act on their own. Students' ideas and creative contributions are influenced through collaboration with peers and instructors. Many mathematics classrooms employ group work as a means to improve learning; Slavin (1996) even called research on collaborative learning, "one of the greatest success stories in the history of educational research" (p. 43). However, in my review of undergraduate mathematical creativity research, studies have almost exclusively investigated the creativity of an individual rather than the creativity of a collaborative group. Some research exists on group mathematical creativity in K-12 students (e.g., Aljarrah, 2020; Levenson, 2011; Sarmiento & Stahl, 2008). Existing studies with undergraduate students have compared group and individual creativity (Molad et al., 2020) and investigated how students construct every-day linear algebra examples in an interview setting (Adiredja & Zandieh, 2020).

Group creativity is the generation of creative ideas by groups when the interactions and inputs of several people are considered (Levenson, 2011). Investigations on group creativity have indicated that a creative product may not necessarily be improved by collaboration (Paulus et al., 2000). Paulus and Yang (2000) claimed that poor outcomes of group creativity may be a result of inattentiveness of group members, difficulty generating ideas while listening to the ideas of others, and lack of incubation time during collaborative work. In collaborative settings wherein diverse individuals work toward a common goal, a variety of backgrounds and knowledge may contribute to the creative product, but it is also possible for diversity of perspectives to be too wide and deter agreement on a common solution (Kurtzberg & Amabile, 2001).

The purpose of the following study is to explore the relationship between creativity in proving and group creativity. This study specifically investigates the assessment of collaborative creativity in proving and seeks to answer the question: how can creativity in proving be assessed in a collaborative setting?

Methods

Participants and Data Collection

Data was collected from an undergraduate Introduction-to-Proof course at a large public southeastern university in the United States. The data used in this study consisted of 25-minute video recordings of two small-group proving episodes during a class meeting in the first week of the course. Group 1 consisted of three students: Nathan (math major), Ganesh (non-degree seeking graduate student), and Matthew (math major); group 2 also consisted of three students: Susan (math major), Mason (computer science major; math minor), and Craig (computer science major; math minor). All names used are pseudonyms.

This course was facilitated in a collaborative, inquiry-based learning environment where small groups of students would work together to prove instructor-provided mathematical conjectures. The two groups investigated in this study were selected using a matched-comparison sampling technique, where each group worked independently to prove the same conjecture: the product of consecutive twin primes is one less than a perfect square. When the class was presented with the proving task, the instructor (a) presented students with definitions for the terms prime number, twin prime, and perfect square, and (b) encouraged students to use alternative representations such as diagrams, pictures, language, and symbols in their group proof. Students worked in their groups of three to prove the given statement and occasionally asked questions of the instructor or graduate assistants. A notable feature of this task is that the statement is also true in a more general context (e.g., for any two integers that differ by two).

This setting and sampling technique provided unique insight to answer my research question as (1) the given task was likely novel to students and thus allowed for an openness in students' approaches to proving the conjecture, (2) the group work occurred during week one of the course, so students were probably unfamiliar with proving and most contributions in terms of proving strategy could be assumed to be novel, or at the very least un-shared, by all members of the group, and (3) both groups were asked to prove the same statement and this provided the opportunity to analyze two different group processes in completing the same task.

Data Analysis

The two video recordings were first transcribed and then coded according to a protocol coding method (Saldana, 2013).The codes were predetermined according to the seven subcategories of the CPR on Proving: *Making Connections* between (1) Definitions/Theorems, (2) Representations, and (3) Examples; and *Taking Risks* according to (4) Tools and Tricks, (5) Flexibility, (6) Perseverance, and (7) Posing questions. Each episode was coded for instances within the group proving pertaining to the subcategories as described in Savic et al. (2017).

The goal of this coding strategy was to identify moments in which the group engaged in creative proving as defined by the CPR. This allowed the group to be viewed as a cohesive unit of analysis and assess their proving process in each subcategory on the spectrum of beginning, developing, and advancing. Descriptions of each of these levels can be found in Figure 1 above.

The final stage of analysis aimed to assess the ability of the CPR on Proving to tell the story of each group's creative proving process. In this stage, I reconsidered the video data and observed important moments and themes which influenced the group's process and may not be conveyed by the CPR on Proving.

Findings

In this section, for each group I present first a holistic general summary of the group's interactions as they attempt to prove the conjecture "the product of consecutive twin primes is one less than a perfect square." I then describe the placement of each group on the CPR on Proving. Then, in the Discussion section of this paper, I compare the findings from my holistic summaries of each proving episode to the impression given by the CPR on Proving.

Group 1 Holistic Summary

Group 1 worked very well together and constructed their proof by challenging, recognizing, and building upon the ideas of their fellow group members. The group began the team's efforts by verifying examples of the statement. Ganesh first challenged the group by proposing that simply generating examples would not be enough to prove the statement and suggested the use of more general principles. Despite this objection, Matthew noticed through the group's list of examples that the perfect square referenced in the statement is the result of squaring the "middle" number of the twin primes used, and he wrote an algebraic representation of the statement: $n^2 - 1 = (n-1)(n+1)$. Ganesh and Matthew argued over how to restrict this equation to be true only for twin prime numbers, and Matthew questioned what would happen if they plugged in a non-prime. Prompted by this, Nathan tested an example using $n = 10$. Matthew then noted that if the statement is actually true for all natural numbers, then the statement would have to hold for the smaller subset of the twin primes; Ganesh did not initially understand Matthew's claim, but Nathan and Matthew explained it to him together. The group proceeded to collectively generalize the statement (i.e., questioning and checking whether the statement would hold for natural numbers, negative integers, real numbers, etc.) until the group work time concluded.

Group 1 Assessment via the CPR on Proving

Figure 2 below provides an aggregation of my coding for group 1's proving attempt in the 25-minute span. Figure 1 provides specific descriptions of each subcategory level.

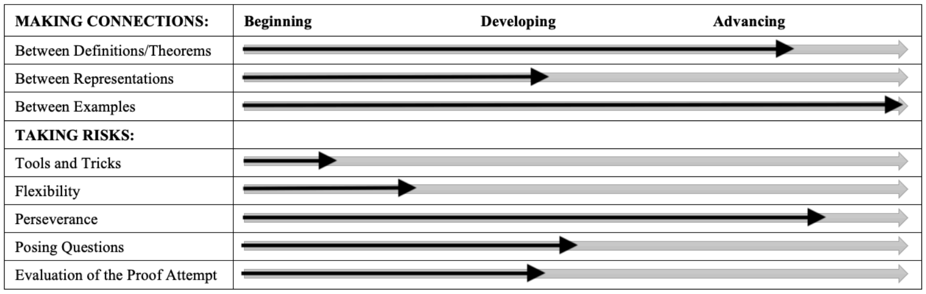

Figure 2. Levels of Group 1's work according to the CPR on Proving.

Using Figure 2, one can observe in which categories group 1 demonstrated strength or weakness. For example, consider the "Between Representations" category. First, group 1 used an algebraic representation when Matthew said:

> If we look at it and n squared is a perfect square, we have n minus 1 times n plus 1, which would be our two prime numbers here, F.O.I.L. it out, and we get n squared minus one.

Group 1 also attempted to use symbolic representation by looking up appropriate symbols for "element of" and "subset" to use in their proof; however, the group did not seem to make use of a conceptual connection between the symbols and their other work. Since group 1 attempted different representations and made some incomplete connections, I coded their work as "developing" in the Between Representations subcategory.

Group 2 Holistic Summary

In contrast to group 1, the students in group 2 spent more of their group time working independently. The first few minutes in group 2 were spent trying to understand the vocabulary in the statement. When Susan attempted to generate an example of the statement, she considered 3 and 5 and observed that the number used to generate the perfect square creates the Pythagorean triple 3, 4, 5. While Susan worked on her idea, Craig was focused on using mathematical symbols and language to rewrite the statement, and Mason worked to verify more examples of the statement. Mason's engagement with the examples led him to observe that the number in the "middle" of the twin primes being the square root of the perfect square mentioned in the statement. While Mason contemplated his idea, Susan admired Craig's rewriting of the statement using symbols for "for all," "therefore," etc. Mason worked to represent the statement algebraically and produced the equation: $n(n+2) = (n+1)^2 - 1$. Mason finally made the conclusion that his equation would work for any number, and hence it would prove the statement for twin primes. Susan challenged this approach, and while she was eventually able to revoice Mason's ideas, she remained confused about the proof at the end of the group's time together. Later during class, Mason presented the group's work to their classmates.

Group 2 Assessment via the CPR on Proving

Figure 3 below provides a summary of the coding for group 2's proving attempts in the 25-minute group work session.

Using Figure 3, one can observe group 2's performance in each category throughout their proving process. For example, consider the "Posing Questions" category. Throughout their collaboration, the members of group 2 posed several clarifying questions. For example, while generating examples, Craig asked, “What’s the prime number after 7?” and later Susan asked her group members and the instructor of the course, “Does one count as a prime number?”

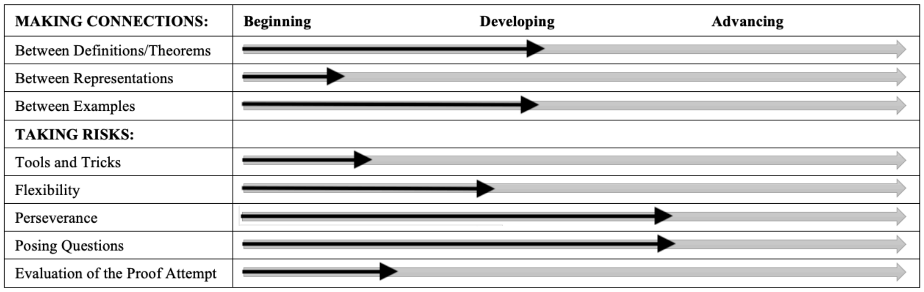

Figure 3. Levels of Group 2’s work according to the CPR on Proving.

Group 2 also demonstrated posing questions while considering possible generalizations of the statement. Mason asked the group, “What if that's true for any two numbers that are two apart? Like...what if that's true for any two numbers?” After posing this question, Susan and Craig largely ignored this idea; nonetheless, Mason proceeded to test his question independently and conclude that the statement could apply to any two numbers with a difference of two.

Although most questions posed were to clarify the given statement and definitions, Mason’s question about generalizing the statement somewhat propelled a conversation regarding the reasoning of the proof. Thus, I coded group 2 between the “developing” and “advancing” levels in the Posing Questions subcategory.

Discussion

Does the CPR on Proving tell the whole story?

The Creativity-In-Progress Rubric on Proving was designed to measure the creativity displayed in an individual’s proving attempt, yet in this study I have attempted to assess a group of students as a unit. Here I describe some observations made through a comparison of the holistic summary of each groups’ work to their respective placement on the CPR.

When reviewing the CPR on Proving assessment of group 1, there are only a few moments neglected in consideration of this group’s holistic story. The coaction of group 1 is not evident by viewing the CPR on Proving assessment of their work. Each student’s individual creative contributions to the proof were deeply intertwined with their teammates, and this should be represented in a rubric of their creative proving process. In contrast to group 1, group 2 did not construct their ideas collectively. I imagine that the CPR on Proving would have been a more appropriate tool for assessing each individual group member of group 2 rather than viewing the group as a unit. Students in both groups frequently posed suggestions or conjectures to their classmates, and this is not acknowledged on the CPR.

Suggestions for Use of the CPR on Proving in Collaborative Settings

With the above observations in mind, I have developed three suggestions for use of the CPR on Proving when applied to a group. My suggestions below are motivated by improving the rubric to enhance its use in revealing mathematical creative abilities in tertiary students through formative assessment and/or reflection. These suggestions may allow the CPR on Proving to help students overcome common roadblocks in proving by reflecting upon their creative process in a group setting.

First, I suggest an additional category titled "Collaboration." The addition of this category to the rubric will require reflection upon the group's ability to recognize and build upon one another's contributions. In the continuum of evaluating collaboration, at the *beginning* level the group members' attempts of the proof are individual. At the *developing* level, group members acknowledge one another's ideas and attempt to produce a cohesive proof. Finally, at the *advancing* level, the group constructs a proof collaboratively and successfully incorporates the contributions of each group member cohesively. For example, in the cases examined in this paper, group 1 would be placed at the "advancing" level, while group 2 would be placed at a high "beginning" level.

The second suggestion for modification of the CPR on Proving is to expand the "Posing Questions" subcategory. I observed in my analysis that students working in a group frequently posed suggestions or conjectures where they may have been posed as questions in an individual setting. I would expand this category to be "Posing Questions/Making Suggestions." For example, in group 1's attempt to generalize the statement, Matthew said:

> "It's a positive number. I'm going to say positive because I don't think it would work with negative... But I don't know, because there's only... Ugh! If we include negatives, then it could be like one and zero. So maybe we can say any nonzero number."

This suggestion prompted a conversation between Matthew and Nathan regarding whether or not the statement would apply to negative numbers similar to how the conversation could have proceeded if Matthew had asked "can we include negative numbers?" The CPR on Proving did not capture this moment because Matthew did not phrase his thought as a question even though his body language and tone indicated he was seeking the groups input on his suggestion.

Finally, when implementing the CPR on Proving in a collaborative setting as a reflective tool, I suggest that students evaluate the proof attempt by first viewing the group as a unit and then using the CPR on Proving to assess their individual contribution to the group. For example, in group 1, Nathan contributed a majority of the examples, Ganesh was strong in making connections to other theorems and flexibility, and Matthew posed important questions to the group. In group 2, Susan and Craig would have had lower scores overall in most categories, while Mason would have had higher scores in most categories. Encouraging group members to examine their contributions may allow them to notice areas for improvement, appreciate contributions of their group members, and learn how to approach proofs more collaboratively.

Future Research

Mathematical creativity is a central tenant of tertiary mathematics education, especially in proof. For this reason, future research should focus on determining how to foster creativity in tertiary mathematics students. Problem posing (Silver, 1997), Model-Eliciting Activities and phenomenon-based learning (Asahid & Lomibao, 2020), and multiple solution tasks (Leikin & Elgraby, 2020) have been conjectured to improve mathematical creativity skills. A clear direction for future research is to examine if collaboration in proving fosters mathematical creativity.

The CPR on Proving has offered a wonderful contribution to the world of undergraduate mathematical creativity in proof by providing a reflective and formative assessment tool to encourage and emphasize creativity. In my experience, as students progress in their mathematics education, they increasingly look to their peers for support and engage in collaboration. My suggestions for future use will support the continued development of the use of the CPR on Proving in a collaborative setting.

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