A Characterization of an Undergraduate Mathematics Instructor's Conception of Learning Through Mathematical Inquiry

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This research report focuses on documenting the conceptions of and relationships between three interrelated components of mathematical learning through inquiry (active learning, meaningful applications, and academic success skills) demonstrated by an experienced mathematician throughout a series of semi-structured clinical interviews concurrent with the participant's engagement in a large-scale professional development initiative. Our analysis revealed that the participant demonstrated stable and coherent conceptions of the three components of mathematical learning through inquiry that were generally resistant to intervention. We reflect on the implications of our analysis for influencing the conceptions of inquiry-oriented instruction held by undergraduate mathematics faculty.

Keywords: Active Learning, Mathematical Inquiry, Professional Development, Teacher Knowledge, Case Study

Introduction

Researchers, professional organizations, and policymakers have emphasized a need for instructors to attend to meaningful student engagement in mathematics classes (CBMS, 2016; Freeman et al., 2014; Kober, 2015; NRC, 2012; NSTC, CSE, 2013; PCAST, 2012; Saxe & Braddy, 2015). Instruction with higher levels of student interaction enhances problem-solving skills (Prince 2004), demonstrates greater conceptual gains (Freeman et al., 2014; Hake, 1998; Svinicki, 2011), and improves retention of information (Dirks, 2011; Prince, 2004; Sokoloff & Thornton, 1997). Although a preponderance of evidence indicates the benefits of active learning, many mathematics instructors struggle to effectively engage students in active learning experiences. Active learning strategies realize their potential when an instructor operates with an explicit understanding of *how* the actions in which students engage might engender the cognitive mechanisms necessary to construct productive meanings for targeted mathematical ideas (Tallman, 2021). Unfortunately, undergraduate mathematics instructors are rarely afforded the opportunity to construct this essential component of pedagogical content knowledge.

Perceptions that mathematics lacks relevance to one's interests and goals is a common deterrent to engaging in active learning. Students with this perspective tend not to appreciate the broader skills they can acquire by studying mathematics. Modeling real-world problems with mathematical tools can provide students with greater opportunities to understand course content and its relevance (Frykholm & Glasson, 2005; Jacobs, 1989; Koirala & Bowman, 2003; Pyke & Lynch, 2005). However, due to a need to cover a broad range of topics, the techniques in entry-level undergraduate mathematics courses are rarely taught in the context of real-world situations. Additionally, even when applied contexts are incorporated into instruction, students often struggle to notice similarities in mathematical structure that would allow them to apply content learned in other contexts (Gick & Holyoak, 1983; Lobato & Siebert, 2002). These observations establish a need for instructors to incorporate relevant applications into mathematics courses for the purpose of both promoting students' positive affect and engaging them in active learning.

Students' conceptions about the origin of mathematical intelligence and the skillset they attribute to being proficient at mathematics have additional implications for their capacity to engage in active learning. Fortunately, students' mindsets are not immutable psychological traits, and specific supports can enable them to reconceptualize what it means to become proficient at mathematics (Middleton, Tallman, Hatfield, & Davis, 2015). Tallman and Uscanga (2020) specified the types of support instructors might provide to foster the positive affect necessary for students to meaningfully engage in active learning. These scholars also cautioned against the ineffectiveness of common efforts to foster students' productive affective engagement in mathematics by reducing these efforts to a list of pedagogical prescriptions without consideration for the mathematical conceptions they are supposed to support.

Taken together, the literature summarized above demonstrates that designing instruction to effectively engage students in active learning is a complicated task for which undergraduate mathematics instructors often receive insufficient preparation, and are thus generally underprepared. To address this need, we designed the Mathematical Inquiry Project (MIP) to support mathematics faculty at all 27 public institutions of higher education in Oklahoma to engage students in learning through inquiry in entry-level mathematics courses. More broadly, the MIP complements principles of organizational change with social learning theory to foster effective, scalable, and sustainable cultural shifts in mathematical learning through inquiry defined in terms of *active learning*, *meaningful applications*, and *academic success skills*.

This research report focuses on documenting one MIP participant's conception of these three interrelated components of mathematical learning through inquiry. In particular, we explored the following research questions: (1) *What conceptions of the three elements of mathematical inquiry and their mutual influence are held by an MIP participant?* (2) *To what extent do these conceptions align with the definitions proposed by the MIP?*

Theoretical Background

Active Learning

At the level of student engagement, the MIP synthesizes constructivist, neo-constructivist, and social-constructivist perspectives, in which conceptual structure is consistently characterized as abstracted from reflection on the structure of one's *actions* to resolve a problem (diSessa, 1982; Gravemeijer, Cobb, Bowers, & Whitenack, 2000; Hickman, 1990; von Glasersfeld, 1995; Piaget, 1970, 1980). The MIP operationalizes this perspective through emphasizing processes that focus students' attention to the nature of a problem, selection of appropriate mathematical tools, application of those tools, and attention to the reciprocal influences of the tool both applied to, and evaluated against, the problem. The MIP definition of active learning is:

> *Students engage in active learning when they work to resolve a problematic situation whose resolution requires them to select, perform, and evaluate actions whose structures are equivalent to the structures of the concepts to be learned.*

Designing this level of student engagement first requires an instructor to become cognizant of the targeted concept's conceptual structure (Tallman & Frank, 2020), and then to purposefully inquire into students' mathematical thinking by listening, interpreting, and respond to the interplay between intuitive and informal ways of reasoning students express.

Meaningful Applications

The MIP leverages educational theory and empirical research that offers insight into how relevant applications might effectively support active learning. One of the most immediate features of our emphasis on applications is that mathematical representations refer to real-world objects and quantities that can be described and imagined to support intuitive reasoning, which is often not elicited when students only encounter abstract representations. This concrete reasoning enables students to engage in mental constructions that can subsequently be represented abstractly by variables, expressions, diagrams, and graphs. The MIP definition of meaningful incorporation of applications is:

> *Applications are meaningfully incorporated in a mathematics class to the extent that they support students in identifying mathematical relationships, making and justifying claims, and generalizing across contexts to extract common mathematical structure.*

Ultimately, for applications to be used effectively, they must foster students' engagement in the mental activity on which they will later reflect to construct targeted understandings of particular mathematical concepts. Additionally, the phrase "generalizing across contexts" should be interpreted within the domain of mathematics and not across other academic disciplines.

Academic Success Skills

Students' active learning is initiated and sustained by components of their affect. The MIP leverages research about growth versus fixed mindsets, the nature of memory and expertise, the integration of academic and social communities, academic identity, stereotype threat, and study skills to equip instructors with the tools to support students active learning of mathematics. We express this amalgam of affective qualities, dispositions, and states as *academic success skills*, which the MIP defines as follows:

> *Academic success skills foster students' construction of their identities as learners in ways that enable productive engagement in their education and the associated academic community.*

Methods

The lead author conducted 11 semi-structured clinical interviews (Clement, 2000; Hunting, 1997) with an experienced professor of mathematics (Robert) from a small, liberal arts university in the Southern United States. The focus of these clinical interviews was to elicit products of Robert's conception of the three components of mathematical inquiry defined by the MIP and to explore their relation to Robert's values, beliefs, and commitments, and instructional goals.

Our data analysis was guided by grounded theory procedures (Corbin & Strauss, 1990; Strauss & Corbin, 2007). The lead author first identified segments of interviews during which Roberts' remarks captured the essence of his conception of one of the three components of mathematical inquiry, or the relationships between them. This initial analysis enabled us to become sensitive to not only *what* Robert said but also *how* he expressed it. From these segments of data, the lead author abstracted Robert's expressed ideas into larger codes and categories (an application of axial coding) and later combined and related these codes and categories into more general clusters, often through several iterations, resulting in a stable set of final themes.

Results

Active Learning

Robert participated in four interviews during which he responded to a series of questions specifically related to active learning (Interviews 1, 2, 6, and 10). During the first interview, Robert described active learning as synonymous with genuine mathematical engagement, which occurs when students solve non-routine problems for which they cannot uncritically apply a rehearsed procedure. At the beginning of the second interview, Robert proposed the following definition of active learning:

Students are engaging in active learning when they are asked to engage with a problem themselves (as opposed to passively observing an instructor solve the problem).

As this definition suggests, Robert's conception of active learning foregrounds the idea of student *engagement*. This definition does not explicitly address the relationship between the mental actions in which students engage and the cognitive structures they might be expected to construct for the targeted concept of a lesson. Towards the end of Interview 2, Robert requested to revise his original definition. His only modification was to replace the word "engage" with "struggle and wrestle." This modification, as well as Robert's comments throughout Interview 2, revealed his perspective that an essential feature of active learning is that it entails students making strategic decisions in the service of overcoming some sort of struggle. Robert considered such strategic and impasse-driven decision-making to be an essential feature of genuine mathematical activity, and thus active learning.

Robert's emphasis on decision-making as a feature of active learning was apparent during a discussion of what might distinguish a student who is engaged in active learning from one who is not. Addressing this question, Robert explained that students "have to be asked to think critically about the problem. They have to make some decisions. They have to make some determinations. So, decision making would be- for me would be the, the, the line." These decisions, Robert clarified, need to be "strong" decisions, and he provided an example from calculus of students struggling to determine whether to apply the method of *u*-substitution instead of integration-by-parts. A few minutes later, Robert concluded: "As long as they're actively, they're, they're trying hard, they're struggling with it, if there's maybe, maybe the defining line should be there has to be a, a level of struggle with a problem." This comment reinforces the claim that Robert considered students' experiencing struggle to be the essential criterion of active learning. There was no evidence in Robert's responses to suggest that he conceived students' struggle as a precondition for engaging in the cognitive activity necessary to construct specific *meanings* for targeted concepts. Generally, Robert gave no indication throughout the series of interviews that his conception of active learning related to an instructor's goals for students' mathematical learning. Instead, Robert's characterizations of the features and requirements of active learning were dominated by his expectation that students' activity should reflect a mathematician's experiences while engaged with a challenging problem. Indeed, Robert's introspection on his own mathematical activity consistently appeared to be the source of the various features of active learning he proposed.

Meaningful Applications

The lead author conducted four interviews with Robert during which he responded to questions specifically related to meaningful applications (Interviews 1, 3, 7, and 9). Robert proposed the following definition of meaningful applications at the beginning of Interview 3:

> *Applications are meaningfully incorporated in a mathematics class when problems are presented that piques student interest and highlights a key concept (or some key concepts) of the lesson.*

There are two fundamental components of Robert's definition: stimulating student interest and highlighting a key concept of the lesson.

When Robert was asked to interpret the MIP definition for meaningful applications in Interview 1, he recognized that this definition was useful for instructors, but "from a student view, meaningful application would be something that, just a problem that they're, that engages them, intrigues them, has to be some kind, spark some kind of interest." One way that a problem might intrigue students is if it relates to them personally or is an applied, real-world problem that enables students to appreciate the applicability of the mathematics they are learning. When asked about his interpretation of the word "meaningful" in the third interview, Robert stated that meaningful is something that "interests me" and has a "hook" to promote interest.

Robert's interpretation of the word meaningful arose from a student perspective (e.g., piques students' interest) as well as an instructor's perspective (highlights a key concept). Robert stated that another interpretation for the word "highlights" is demonstrates: "Demonstrates is (*pause*), it brings to (*pause*), it shows the, shows the usefulness of these concepts. It demonstrates why, why we're doing what we're doing." Robert offered an illustration for how an instructor might highlight or demonstrate the usefulness of a concept:

> If I can come with an application, a problem that forces you, really encourages you to use one over the other, that's a meaningful application, right. If I, if I try to teach you a shell method, right, usually a shell after the washer method, right, but if I give you a problem where I, where students can just as, just as easily solve it using the washer method, then what's the point, right?

Robert echoed a similar sentiment later in the interview, stating that if he were teaching the shell method he would "steer away" from problems that can be solved equally easy using either the shell method or the washer method (unless he wanted to highlight that sometimes either approach is appropriate).

Academic Success Skills

The lead author conducted three interviews with Robert during which he responded to questions specifically related to academic success skills (Interviews 1, 4, and 8). At the beginning of Interview 4, Robert constructed his definition:

> *Academic Success Skills are behaviors/actions that help people/students succeed academically (i.e., in their studies/research). Examples include: detailed note taking, a sense of curiosity, the grit/determination to tackle/solve a problem—from several approaches if necessary, and to think critically.*

Robert's conception of academic success skills centered around thinking critically and exercising grit and tenacity to persist in satisfying curiosity. According to Robert, *thinking critically* entails making "deliberate decisions" and operating *intentionally* when solving problems as opposed to using a particular technique because peers used it, the book encouraged it, or it proved useful in another context. Critical thinking is a key facet of the academic success skills Robert values most:

> For me, the most important academic success skill is being engaged, and being, uh, curious, and being, and just really getting, getting down and really exploring the concept,

> right, having the grit, uh, and tenacity to, to, work on the problem. I, that to me, that, for me, hands down, that's the most important.

Robert's latter statement offers insight into how he might develop tasks to support students' academic success skills. He expects that the affective qualities he values in students can be reinforced by engaging them in tasks that elicit productive struggle, and encouraging them to reflect on their attempts to solve the problem.

While students may be able to enhance their determination from engaging in tasks that facilitate productive struggle, the interviewer asked Robert if the ways in which an instructor teaches a *specific mathematical topic* can promote students' curiosity, tenacity, or grit. Robert's response emphasized how instructors' actions can be *problematic* for promoting these affective characteristics, stating that making math "mechanical" makes it become artificial and tedious.

Throughout the series of interviews, Robert frequently described active learning as dependent upon students' curiosity and tenacity. The interview data consistently indicated that Robert's conception of active learning was closely connected to his image of mathematical problem solving and the curiosity and tenacity that initiates and sustains it. Robert reasoned that curiosity and tenacity are essential to active learning since the former is both the origin of genuine mathematical problems and the affective state that compels a student to want to solve a problem. Additionally, Robert expressed that tenacity is required to persevere through the struggle inevitably encountered when reasoning about a novel problem. He explained that curiosity and tenacity is "what made me successful in my schooling," again revealing Robert's reflection on his mathematical activity to infer essential features of active learning and their relation to students' affect.

Robert clarified his image of the relationship between active learning and students' academic success skills during Interview 2:

> My style of teaching is for students to struggle with a problem, understand why that problem is hard and why that problem is interesting, then I will come back around and show them a way that is easier. Then they can learn to appreciate the new knowledge that I am trying to teach them.

This excerpt suggests that Robert considered active learning in terms of students' engagement in the precise activity that results in their experiencing an intellectual need for the mathematical content that he will eventually present to them. Robert's comments indicate that he valued this type of activity because it can ultimately position students to more intently and purposefully absorb the mathematical meanings, skills, and strategies he communicates. That is, active learning makes students more receptive to *perceiving* the mathematics that Robert conveys and/or demonstrates. This conception of the relationship between active learning and students' affect stands in contrast to the MIP definition of active learning, which views students' activity as the experiential basis of their knowledge construction through abstraction. The excerpt above reveals Robert's expectation that the insight, method, or strategy required to solve a problem should ultimately be provided by the instructor, rather than constructed by the students through their mathematical activity.

Summarizing Robert's conception of the relationship between meaningful applications and active learning, he described meaningful applications as providing contexts that can stimulate students' curiosity and then require them to be tenacious and perseverant to solve a contextual problem. There was no evidence in Robert's remarks to suggest that he interpreted "meaningful" as a reference to the meanings an instructor expects their students to construct.

Discussion and Implications

Robert' conception of active learning centered around student engagement in thinking critically, making decisions, and wrestling with problems. According to Robert, active learning can occur in many forms, and the distinction between students who are engaged in active learning and those who are not depends on students making decisions and struggling to solve non-routine problems. A primary feature of Robert's conception of meaningful applications includes a context that *cultivates students' interest*. Robert also explained that a meaningful application should also *highlight the key concept* of the lesson, which could involve demonstrating the usefulness of a particular technique (e.g., disc vs. shell method in calculus). Robert's conception of academic success skills focused on students acting on their curiosity with grit, determination, tenacity, and critical thinking skills to solve a novel problem.

While Robert claimed that his conceptions of the three components of inquiry had been influenced through his involvement in MIP activities, his comments throughout the series of clinical interviews demonstrated that he underemphasized and perhaps undervalued the importance of designing tasks that promote students' construction of particular mathematical meanings. Additionally, Robert's remarks revealed his inattention to the nature and development of students' conceptions.

A fundamental distinction between Robert's conception of active learning compared to the MIP definition is that Robert considered struggle, effort, and strategic decision-making as sufficient criteria for engaging in active learning, independent of the *meanings* he expected students to construct. Similarly, Robert conceptualized the incorporation of meaningful applications as having primary implications for students' affective engagement, specifically motivation and interest. In his own practice, Robert explained that he motivates students by providing *interesting* contexts or by demonstrating the *usefulness* of a particular problem-solving approach.

Notably, Robert's comments throughout the series of interviews highlight a fundamental epistemological distinction: that he underemphasized, devalued, or was inattentive to the instructor's role in designing tasks informed by conducting a *conceptual analysis* (Thompson, 2008) for the purpose of enabling students to progress through a *hypothetical learning trajectory* (Simon & Tzur, 2004). While promoting students' affective qualities is important, particularly related to academic success skills, the MIP definition is centered around supporting students' construction of operative mathematical schemes by identifying and clarifying the nature of the mental actions and conceptual operations required to construct an understanding of a mathematical idea in a particular way.

Importantly, this discussion is neither intended to diminish nor devalue features of Robert's instructional design or pedagogical practices, nor to criticize his interpretation of three elements of inquiry proposed by the MIP. Rather, we offer these distinctions to highlight the potential for Robert's conceptions to be extended and refined to include attention to epistemological considerations of students' mathematical learning. Our results suggest that intensive measures are required to disrupt and modify Robert's established, stable, and coherent conceptions of the three components of mathematical inquiry.

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