An Activity Theory Approach to Mediating the Development of Metacognitive Norms During Problem Solving

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Metacognition has long been identified as an essential component of the problem-solving process. Research on metacognition and metacognitive training has historically adopted an acquisitionist view. This study takes a participaionist lens by considering metacognition as a habit of mind or dispositional tendency. Problem-solving habits of mind can be viewed as normative ways of thinking to which students become attuned by participating in authentic problem-solving situations. This study explored one such situation, in which portfolio problem-solving sessions and write-ups were used to mediate metacognitive thinking. Periodically, students worked together on non-routine problems and submitted individual write-ups documenting their judgement and decision-making processes. Analysis utilized Activity Theory, which operationalizes the participation structure of a classroom, to document the nonlinear development of classroom metacognitive norms during problem solving. Micro-analysis revealed a shift from product- to process-oriented metacognitive norms. Macro-analysis situated these results, highlighting social mediators of activity and contradictions as catalysts for change.

Keywords: Metacognition, Problem Solving, Norm Development, Activity Theory

Introduction and Motivation

The importance of problem-solving practices has been emphasized and studied extensively (NCTM, 2010). Although literature has identified metacognition as a key component of the problem-solving process (e.g. Schoenfeld, 1985), metacognition remains undertheorized and under-studied in its application to classroom communities (Carroll, 2008). While the importance of prolonged metacognitive instruction embedded in content matter has been emphasized (Lester, Garofalo, & Kroll, 1989; Veenman, Van Houte-Wolters, & Afflerbach, 2006), most metacognitive research has overlooked the crucial impact of sociocultural contexts and learning environments in its development (Larkin, 2015). Further, metacognitive research, with foundations in cognitive information processing theory, has taken an almost exclusively acquisitionist (Sfard, 1998) approach to metacognition, where metacognitive skills are decontextualizable commodities (products) to be transmitted to students. As such, research concerning the teaching and learning of metacognition has been limited in its practical classroom application by overlooking the process characteristics of metacognitive thinking. There is a difference between "*knowing-about*" and "*knowing-to act in the moment*" (Mason & Spence, 1999). Becoming a skillful problem solver means coming to know the nuanced ways of *doing* or acting (as opposed to *having*) in authentic mathematical problem-solving situations.

Rather than viewing metacognitive knowledge and skills as objects to be transmitted, this research study took a complementary approach by appealing to metacognition as a habit of mind (Costa & Kallick, 2000), a disposition toward certain ways of acting during the problem-solving process. Taking a participationist (Sfard, 1998) view of the teaching and learning of metacognition, a skilled problem solver must both "communicate in the language of the community and act according to its particular norms" (p. 6). Problem-solving habits of mind, such as metacognition, can be viewed as normative ways of thinking or acting within the "skilled problem solver" community of practice. Through legitimate peripheral participation (Lave & Wenger, 1991), students become attuned to these normative, habitual tendencies or dispositions, eventually transforming their own habits of mind as they become full participants (i.e., skilled problem solvers) in this community. This theoretical approach requires understanding the process of student participation in metacognitive thinking, with attention to the contexts that afford or constrain such dispositional transformations toward full participation.

Accordingly, the purpose of this study was to investigate the use of portfolio problems (defined below) as a mediator of participation in metacognitive thinking during problem solving, delivering a prolonged intervention embedded in mathematics content called for by Lester, Garofalo, and Kroll (1989). Students worked on six portfolio problems throughout the semester, each of which consisted of two main parts: small group problem-solving sessions in class and individual write-ups. Except for the first problem which only involved one session, groups worked on a given problem over two in-class sessions, with each session lasting roughly one-third of a class period. These non-routine problems were chosen to align with the NCTM's (2010) "worthwhile-problem criteria," and to increase the likelihood that a solution path was not immediately known to students. Further, problems were selected with key mathematical ideas directly related to the content unit in which the problem was presented. The instructional team encouraged students to record their work and observations or questions on scratch work. Students wrote in different colored pens to identify individual contributions. This scratch work was emailed to each group after class, and students were expected to continue working on the problem outside of class. Students then submitted individual write-ups documenting a revised solution that included mathematical justification and reasoning, as well as their judgement and decision-making processes during the entire problem-solving attempt, from initial thoughts to final result. For example, students might include questions they asked themselves, or a discussion of why they employed or abandoned a particular representation or problem-solving strategy.

Theoretical Framing

In studying students' attunement to normative ways of thinking, one must consider that the natural, purposeful activity within a classroom creates a microculture of negotiated activities and interactions among students and the teacher (Lave & Wenger, 1991). Over time, normative behavior emerges, but the interpretation and function of these norms change through iterations of negotiation. Consequently, metacognitive norms may develop in a way so that the resulting activity is not necessarily identical to that intended by the teacher. Thus, the focus of investigation turns to the development of a classroom community's normative metacognitive activity during problem solving. This necessitates an appropriate framework to document the nonlinear development of classroom problem-solving norms.

Third-generation Activity Theory (Engeström, 1987), which is conducive to a participation metaphor for learning (Barab, Evans, & Baek, 2004), was used in the present study as an analytic framework for systematic investigation. Activity Theory accounts for the complex interaction between the individual and community by expanding Vygotsky's (1978, 1986) notion of mediated activity to include additional social mediators (Engeström, 1987) (Figure 1). Individuals or groups of individuals form a motivated, object-oriented activity system, where the entire activity system forms the unit of analysis. An activity system dynamically transforms, expanding or changing qualitatively over (relatively long periods of) time through adaptation to contradictions or tensions (Engeström, 1987). In the context of this study, students in a first-year mathematics content course for pre-service elementary teachers formed one activity system, while an instructional team, consisting of myself and the instructor of record, created a "culturally more advanced" (Engeström, 1987) activity system that interacted with the student activity system.

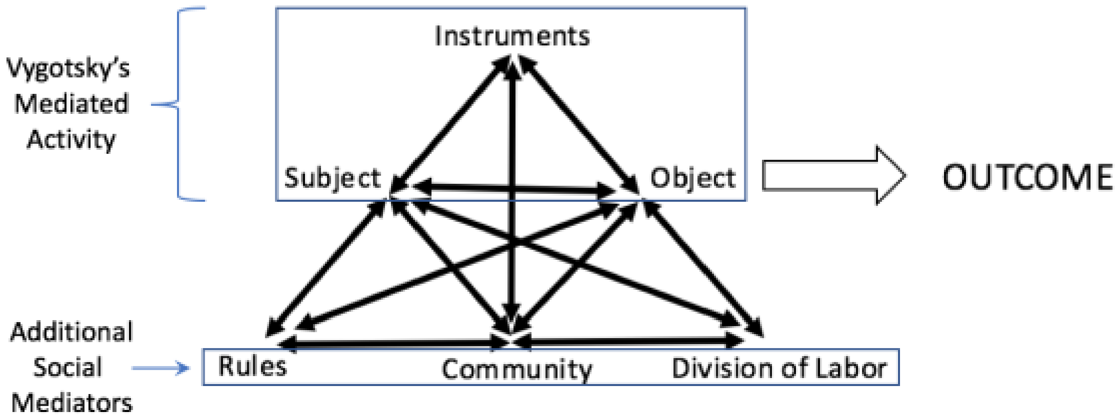

Figure 1. Vygotsky's mediated activity embedded within the expanded activity triangle.

In the context of documenting the process of classroom norm development, (Third-generation) Activity Theory is particularly advantageous. Specifically, Activity Theory provides:

1) *Operationalization*: Activity Theory operationalizes the participation structure of a classroom community for detailed, systematic investigation (described in the following Methods section).
2) *Attention to Reflexivity*. The classroom collective and individual students influence each other in a cycle of negotiation and influence (see Ernest, 2010). By framing students and the teacher as interacting activity systems, Activity Theory provides explicit language with which to document this nuanced, reflexive interaction over time.
3) *Expansion, and Horizontal Expansion.* Classroom norms are not pre-established, unchanging concepts, and their development can be influenced by students. Further, students' learning and development is not necessarily vertical, from "lower" to "higher" levels of competence. Activity Theory accounts for student growth and potentially non-vertical, or horizontal growth, through the process of expansive transformation, which occurs "when the object and motive of the activity are reconceptualized to embrace a radically wider horizon of possibilities than in the previous mode of the activity" (Engeström, 2001, p. 137).
4) *Process-Focused Interaction of Social Activity and Individual Actions*. Activity Theory focuses on the process of interaction over time, allowing for documentation of the transformational process of reflexive interaction between covert social activity affecting participation and individual actions of participation.
5) *Contradictions as Catalysts for Change*. Characterizing system dynamics through contradictions and tensions is a powerful means for interventionist-motivated design research. This study capitalized on portfolio problems as a mediating instrument to create a purposeful contradiction between the object/motive pair of the student activity system and the object/motive pair of a culturally more advanced form (the teacher activity system).

Methods

This qualitative research study, grounded in the aforementioned theoretical perspective, was guided by the research question: What is the role of portfolio problems as a mediating instrument in the development of normative metacognitive activity during problem solving, within an undergraduate mathematics classroom community of pre-service elementary education majors? To address this question, sub-questions were posed: (a) What metacognitive actions during problem-solving become normative activity? (b) What contradictions or tensions exist within the classroom community that catalyze the development of such normative metacognitive activity during problem solving? and (c) What actions of the teacher influence, positively or negatively, the development of such normative metacognitive activity during problem solving?

Six qualitative data sources were collected in the 15-week semester: (1) video- and audio-recorded classroom sessions, (2) three videotaped, semi-structured individual interviews with 13 of the 23 students at the beginning, middle, and end of the course, (3) two audio-recorded interviews with the instructor of record, (4) students' written artifacts (assignments, exams, and portfolio-problem submissions and scratch work) collected before grading, (5) recorded planning sessions of the instructional team, and (6) journal reflections written by each member of the instructional team after each class session. The first data source, recorded classroom sessions, was utilized for micro-analysis, while all data sources were used for macro-analysis.

The first and second student interviews (data source (2)) had three parts. First, students were asked questions targeting their beliefs about mathematics, mathematical problem solving, and perceptions of the course. Students then worked, thinking aloud, on non-routine problems related to course content. This portion of the interview provided a reference point for students to discuss their problem-solving activity more generally. Finally, students compared their problem-solving attempts during the interview with their "typical" problem-solving activity in the course, as well as the problem-solving activity of course instructors, other students in the course, and other courses. The third interview did not include problem solving, but was a series of questions asking students to reflect on their experiences in the course.

Two levels of analysis were employed: a micro-analysis of language-mediated discourse [the upper boxed portion of the activity triangle in Figure 1], followed by macro-analysis using Engeström's expanded activity triangle to highlight tensions within the activity system (Jaworski & Potari, 2009). Micro-analysis served to address research sub-question (a) by identifying metacognitive actions (adapted from Carlson & Bloom, 2005) present during each of the in-class portfolio problem-solving sessions (Table 1). Recalling that a participation metaphor for learning was adopted in this study, the focus was on students' real-time *actions*. Thus, while written artifacts of students' judgement and decision-making processes were collected as part of the portfolio problems, only those actions demonstrated in situ were documented to evidence normative metacognitive activity.

Table 1. Metacognitive actions identified during portfolio problem-solving sessions

MA 1.	Mathematical concepts, knowledge, tools, and facts are assessed and considered
MA 2.	Various solution approaches or strategies are assessed and considered
MA 3.	Validity/reasonableness of solution process is assessed/considered/tested
MA 4.	Results are assessed/tested/considered for their reasonableness/validity
MA 5.	Reflects on the efficiency and effectiveness of cognitive activities
MA 6.	Manages emotional responses to problem-solving situation

Macro-analysis situated micro-analysis results, using a six-step method (Jonassen & Rohrer-Murphy, 1999) to describe various components of the student activity systems (Table 2). The student activity system was analyzed at multiple points throughout the semester to document potential change over time. Contradictions and tensions within the student activity system, as well as between the student and instructional team activity systems, were detected in the final step of macro-analysis, addressing research sub-question (b). As an additional part of both micro- and macro-analyses, actions taken and decisions made by the instructional team potentially impacting the development of metacognitive norms were identified, addressing research sub-question (c).

Table 2. Six Steps for Analyzing an Activity System (Jonassen and Rohrer-Murphy (1999))

Step 1.	*Clarify the purpose of the activity system.* Describe the motives and conscious goals of the activity system.
Step 2.	*Analyze the activity system.* Define the subject, object, community, division of labor, and rules.
Step 3.	*Analyze the activity structure.* Delineate the hierarchy of activity, concrete actions, and automatized operations.
Step 4.	*Analyze tools and mediators.* Describe the tools, rules, and roles of participants that mediate activity within the system.
Step 5.	*Analyze the context.* Characterize the internal, subject-driven and external, community driven contextual bounds.
Step 6.	*Analyze activity system dynamics.* Step back from the delineated activity system to describe and assess how components affect each other.

Results and Discussion

Micro-analysis results, addressing research sub-question (a), indicated a shift in function of metacognitive thinking during problem solving. Over the course of the semester, the normative metacognitive activity employed during portfolio problem-solving sessions transformed from a retroactive focus on checking answers (*products*), to a proactive focus on the evaluation of the problem-solving *process*, especially the consideration of various solution approaches, tools, and strategies. Figure 2 broadly illustrates this change, where Metacognitive Action 4 (MA4) was prevalent at the beginning of the semester, but dissipated in use over time, with process-focused actions becoming dominant (e.g., MA2, MA3). By the end of the semester, students recognized this transition away from reflecting *only* at the end of a problem-solving attempt, as highlighted in the following student quote taken from the final interview:

> I've just been able to be actively engaged in the problem, realizing what I'm doing. Rather than just like, ‘Well, this is the first step and second step,’ and then afterwards I'm like, ‘Oh, that was wrong, and that was wrong.’

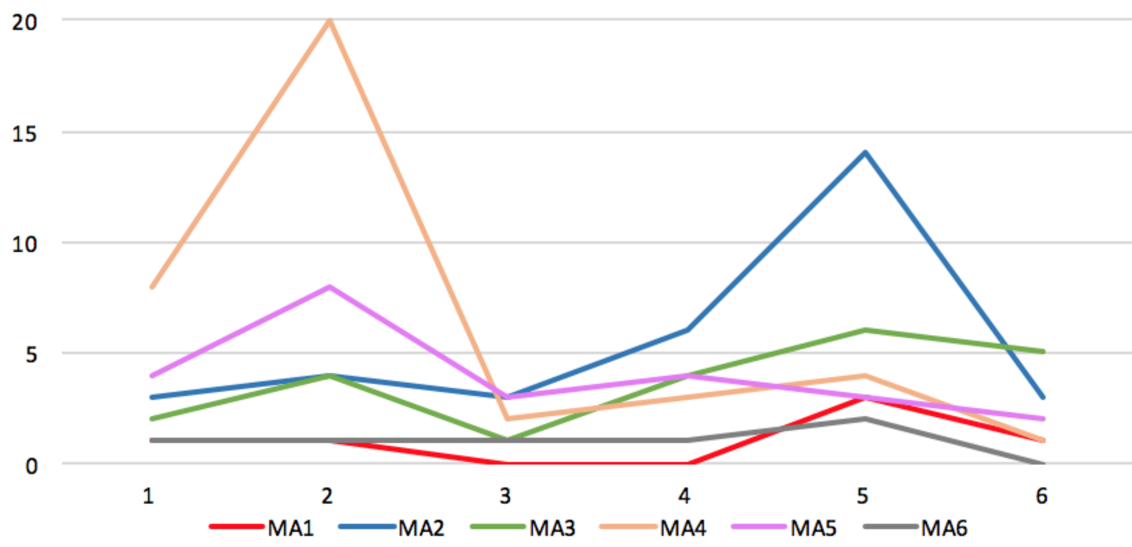

Figure 2. Total occurrences of Metacognitive Actions during the six in-class portfolio problem-solving sessions.

Macro-analysis situated these results, revealing contradictions that shaped the development of the normative metacognitive activity from micro-analysis, directly addressing research sub-question (b). Notably, the introduction of portfolio problems as a mediating instrument for problem solving constituted a significant catalyst for change. Students identified all aspects of the portfolio problems (in-class problem-solving sessions, scratch work, and submitted write-ups) as contributing to the awareness of their thinking during the process of problem solving. The portfolio problems also contradicted many students' motives and expectations for the course. While students anticipated learning to teach mathematics, the focus of the course was for students to improve as mathematical thinkers themselves. The non-routine, open nature of the portfolio problems brought this tension to the fore, encouraging students to adjust their course goals and embrace opportunities for personal development.

Additionally, instructor actions contributing to the development of metacognitive norms were identified during both micro- and macro-analyses, directly addressing research sub-question (c). The instructional team encouraged students to focus on process over product, generalize their problem-solving solutions and methods, and look for commonalities across problem contexts. Further, the team attempted to make overt the typically invisible mediators of mathematical problem solving. While this motive of the instructional team was consistent throughout the course, portfolio problems provided a rich setting within which to have these conversations, amplifying the influence of teacher actions. For example, the instructional team noticed students' increased frustration that they were not finding solutions to the portfolio problems. The team used this as an opportunity to discuss perseverance in the problem-solving process, using a video describing Andrew Wiles' lengthy process for generating a proof of Fermat's Last Theorem to aid in facilitating this discussion. This discussion allowed the class to both focus on the process of problem solving, and see that perseverance is an important aspect of this process.

In this study, portfolio problems contributed to students' shift in focus from reflection on the answers or outcomes (*products*) of a problem-solving attempt, to metacognitive thinking during the entire *process* of problem solving. While an inquiry-oriented course design and complementary teacher actions facilitated this shift, the portfolio problems accelerated the effects of these actions by creating contradictions or tensions as catalysts for student transformation. The intervention design in this study, with portfolio problems directly related to course content and used throughout the entirety of the course, supports the claim that metacognitive instruction must be embedded as part of the classroom culture. Additionally, Activity Theory proved useful as a framework for analysis, as it explicated the role of portfolio problems as facilitators of change through the creation of contradictions or tensions. This characterization is a powerful tool for intervention-based design research intended to create *purposeful* contradictions that can lead to productive beliefs (NCTM, 2014) about the teaching and learning of mathematics.

References

Barab, S.A., Evans, M.A., & Baek, E.O. (2004). Activity theory as a lens for characterizing the participatory unit. In D.H. Jonassen (Ed.), *Handbook of research on educational communications and technology* (pp. 199-213).

Carlson, M. P. & Bloom, I. (2005). The cyclic nature of problem solving: An emergent multidimensional problem-solving framework. *Educational Studies in Mathematics*, *58*(1), 45-75.

Carroll, M. (2008). Metacognition in the classroom. In J. Dunlosky & R. Bjork (Eds.), *Handbook of metamemory and memory* (pp. 411-427). New York, NY: Psychological Press.

Common Core State Standards Initiative. (2010). Common core state standards for mathematics. Retrieved from http://www.corestandards.org/assets/CCSSI_Math%20Standards.pdf

Costa, A.L. & Kallick, B. (2000). *Discovering & exploring habits of mind.* Alexandria, Va.: Association for Supervision and Curriculum Development.

Engeström, Y. (1987). *Learning by expanding: an activity-theoretical approach to developmental research*. Cambridge University Press.

Engeström, Y. (2001). Expansive learning at work: Toward an activity theoretical reconceptualization. *Journal of education and work*, *14*(1), 133-156.

Ernest, P. (2010). Reflections on theories of learning. In B. Sriraman & L. English (Eds.), *Theories of mathematics education: Seeking new frontiers* (pp. 39-47). Berlin: Springer Verlag.

Jaworski, B., & Potari, D. (2009). Bridging the macro-and micro-divide: Using an activity theory model to capture sociocultural complexity in mathematics teaching and its development. *Educational Studies in Mathematics*, *72*(2), 219-236.

Jonassen, D.H., & Rohrer-Murphy, L. (1999). Activity theory as a framework for designing constructivist learning environments. *Educational Technology Research and Development*, *47*(1), 61-79.

Larkin, S. (2015). An approach to metacognition research. In R. Wegerif, L. Li, & J. C. Kaufman (Eds.) *The Routledge International Handbook of Research on Teaching Thinking* (pp. 254-265). Routledge.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Lester, F.K., Garofalo, J., & Kroll, D.L. (1989). Self-confidence, interest, beliefs, and metacognition: Key influences on problem-solving behavior. In D. McLeod & V. Adams (Eds.), *Affect and mathematical problem solving* (pp. 75-88). New York, NY: Springer.

Mason, J., & Spence, M. (1999). Beyond mere knowledge of mathematics: The importance of knowing-to act in the moment. In *Forms of Mathematical Knowledge* (pp. 135-161). Springer Netherlands.

National Council of Teachers of Mathematics. (2010). *Problem solving research brief: Why is teaching with problem solving important to student learning?* Reston, VA: National Council of Teachers of Mathematics.

National Council of Teachers of Mathematics. (2014). *Principles to actions: Ensuring Mathematical success for all.* Reston,VA: National Council of Teachers of Mathematics.

Schoenfeld, A. (1985). *Mathematical problem solving*. Orlando, Fla: Academic Press.

Sfard, A. (1998). On two metaphors for learning and the dangers of choosing just one. *Educational Researcher*, *27*(2), 4-13.

Veenman, M.V., Van Hout-Wolters, B.H., & Afflerbach, P. (2006). Metacognition and learning: Conceptual and methodological considerations. *Metacognition and Learning*, *1*(1), 3-14.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Cambridge, MA: Harvard University Press.

Vygotsky, L.S. (1986). *Thought and language* (A. Kozulin, Ed.). Cambridge, MA: MIT Press.