INVESTIGATING THE INTERACTION BETWEEN TEACHER MATHEMATICS CONTENT KNOWLEDGE AND CURRICULUM ON INSTRUCTIONAL BEHAVIORS AND STUDENT ACHIEVEMENT

by

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A DISSERTATION

Presented to the Department of Special Education and Clinical Sciences
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

June 2021

DISSERTATION APPROVAL PAGE

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Title: Investigating the Interaction between Teacher Mathematics Content Knowledge and Curriculum on Instructional Behaviors and Student Achievement

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Degree awarded June 2021

DISSERTATION ABSTRACT

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Doctor of Philosophy

Department of Special Education and Clinical Sciences

June 2021

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Low mathematics achievement in the United States has led to a push to increase the quality of mathematics instruction. Policy efforts in mathematics have typically focused on increasing teachers' mathematical content knowledge (MCK), with the goal of increasing teacher quality, and in turn increasing student mathematics learning. While research indicates that teacher MCK is predictive of student mathematics achievement gains (Hill et al., 2005), mathematics PD programs focused on increasing teacher MCK have been largely ineffective at increasing student mathematics achievement (e.g., Garet et al, 2016). An alternative approach to increasing student mathematics achievement is to investigate curricula that can be effectively used by teachers with a range of MCK (Agodini & Harris; Stein & Kaufman, 2010).

The current study contributed to this line of research using data collected for the Early Learning in Mathematics (ELM) large-scale efficacy trial (Clarke et al., 2015) to investigate two research questions: (1) Does curriculum (ELM vs. business-as-usual) moderate the association between teacher MCK and instructional behaviors?, and (2) Does curriculum (ELM vs. business-as-usual) moderate the association between teacher MCK and student mathematics achievement gains in kindergarten? Participants included kindergarten students (*n* = 2,598) and their teachers (*n* = 130) in classrooms randomly assigned to use the ELM core kindergarten curriculum or business-as-usual, district-approved curricula. Multiple regression analyses demonstrated that the nature of the Teacher MCK x Curriculum interaction varied across instructional behaviors examined. Two-level hierarchical linear models revealed that there was not a significant Teacher MCK x Curriculum interaction on student mathematics achievement gains, and main effects models indicated a small but negative effect of teacher MCK and a positive effect of ELM. Results are discussed in the context of implications for future research and practice.

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ACKNOWLEDGEMENTS

I would like to express gratitude to my advisor, Ben Clarke, for his guidance throughout the development and completion of this dissertation, along with his strong mentorship throughout my graduate training. His encouragement, support, and advice over the years has been invaluable to my professional growth in graduate school. I also wish to express my deepest appreciation to Derek Kosty, who was an instrumental part of this process, for his time and patience reviewing my work. I would also like to extend my thanks to Hank Fien and Joanna Goode for serving as valuable members on my committee. This investigation was supported by the Institute of Education Sciences, U.S. Department of Education, through Grants R305K040081 and R305A080699 awarded to the Center on Teaching and Learning at the University of Oregon and Pacific Institutes for Research.

For my mother and stepfather who taught me to pursue my passions above all else,
For my father, for his lessons of patience, dedication, and a love for the outdoors,
For my siblings, who are my constant inspiration,
For my partner, for his endless support, humor, and sense of adventure.

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CHAPTER I: INTRODUCTION

International comparisons of achievement in mathematics reveal a trend of American students performing poorly compared to students in similarly resourced countries (Beaton et al., 1996; Gonzales et al., 2000, Schmidt et al., 2002). As recently as 2015, Trends in International Mathematics and Science Study (TIMSS) data revealed that on average, fourth grade students in the United States underperformed in mathematics compared to several East Asian and European nations including Singapore, Japan, Norway, and regions of China (Mullis et al., 2016). Looking within the United States, less than half of fourth grade students met the proficient benchmark on the most recent administration of the National Assessment on Educational Progress – a finding that has gone unchanged for decades (NAEP, 2019).

When disaggregating the most recent NAEP data across student subgroups, students from underserved populations continue to score drastically below their peers. NAEP (2019) results indicate that the achievement gap widened between the highest (90th percentile and above) and lowest (10th percentile and below) performing students from 2009 to 2019. Only 16 percent of English learners (ELs) in Grade 4 scored at or above the proficient benchmark in comparison to 44 percent of non-EL students (NAEP, 2019). Opportunity gaps are also evident for students from certain racial minority backgrounds, students from low socioeconomic backgrounds, and students with disabilities (Lee et al., 2007; NAEP, 2019). These findings are particularly concerning given that strong mathematical knowledge leads to important academic and occupational opportunities later on (Claessens & Engel, 2013) and that an increasing number of employment opportunities, such as those in the STEM (science, technology, engineering, and mathematics) fields, require a high level of mathematical knowledge (National Science Board, 2008).

In light of findings indicating that in general, U.S. students underperform in mathematics and that large discrepancies are evident between students across different subgroups, policymakers and leaders in educational reform have continually circled back to the question: How can we move the dial on student mathematics achievement? One common response to this question looks to teacher quality, which has consistently been implicated in educational research as a major factor contributing to students' academic performance (Darling-Hammond & Berry, 2006; Hattie et al., 2016; Lasley et al., 2006; Terhart, 2011), and as a result has been a long-standing target for improving student outcomes in mathematics. The executive summary of the 2000 Commission on Mathematics and Science Teaching for the 21st Century (CMST) report argued that "the most powerful instrument for change, and therefore the place to begin, lies at the very core of education-*with teaching itself"* (p. 7). Parallel calls in the State of the Union addresses from President Bush in 2006 and President Obama in 2011 to expand the role of the federal government in producing higher-quality mathematics teachers speak to the persistent concern regarding teachers' preparedness to effectively teach mathematics (Remarks by the President in State of Union Address, 2011, January 25; The State of the Union, 2006, January 31).

One approach from the early 2000's and onward to increase teacher quality in mathematics has been through teacher professional development (PD) programs and teacher training initiatives. This is reflected in policies such as the No Child Left Behind (NCLB) Act of 2001 (NCLB, 2002) and President Obama's call to train 100,000 STEM teachers in 10 years (The White House, Office of the Press Secretary, 2010). A conservative estimate of the amount that K-12 schools spend annually on teacher PD lands in the tens of billions of dollars (Kraft et al., 2018). PD initiatives have become not only commonplace but are often mandated by districts (Cavell et al., 2004; Perez & Kumar, 2018). Notably, the vast majority of teacher PD programs in mathematics focus on deepening teachers' understanding of mathematics content as a means to improve teacher quality and lead to increased student learning (Jacob et al., 2017; Garet et al., 2011; Garet et al., 2016; Santagata et al., 2011). As described by Ball et al. (2005), "To implement standards and curriculum effectively, school systems depend on the work of skilled teachers who understand the subject matter" (p. 14).

An alternative approach to improve mathematics instruction is targeting the quality of core mathematics curricula and the inclusion of curricular supports to enable effective implementation for teachers across a range of skillsets (Stein et al., 2007; Remillard et al., 2014). Researchers interested in curriculum implementation are moving toward identifying specific curricular features that may guide teachers to implement programs more effectively (Remillard et al., 2014; Stein & Kaufman, 2010). For example, curricula that provide scripting for teachers may allow for the use of precise and consistent mathematical language during instruction (Remillard & Reinke, 2012).

The current study investigated two areas targeted in mathematics reform and their associations with instructional behaviors and student mathematics achievement: teachers' mathematics content knowledge (MCK), and core mathematics curricula. The following literature review provides an overview of the associations of teacher MCK and student mathematics achievement, including outcomes of teacher PD programs targeting teacher

MCK. Additionally, curricular features associated with greater student mathematics outcomes are reviewed, along with the impact of evidence-based curricula on student mathematics achievement. Finally, two studies investigating interaction effects between MCK and curriculum are summarized.

The Role of Teacher MCK in Research and Policy

Initial forays into examining the association between teacher MCK and student mathematics achievement have demonstrated that more knowledgeable teachers tend to have students that make greater gains across the course of the school year (Hill et al., 2005; Metzler & Woessman, 2012). However, the complexities of this relationship are underexplored in the research, with researchers using a variety of modalities to measure teachers' MCK and finding varying levels of its association with student mathematics achievement. In the existing literature, common proxies of MCK have included tracking teachers' advanced mathematics courses or mathematics education courses, years of experience teaching, degrees or certifications in mathematics, or scores on basic mathematics skills tests (Mullens et al., 1996; Rowan et al., 1997; Telese, 2012). While reviews of this literature suggest that these variables are associated with student mathematics achievement (Greenwald et al., 1996; Wayne & Youngs, 2003), a common critique is that there may be underlying factors contributing to the associations between these variables and student mathematics achievement (Hill et al., 2005).

In mathematics, there may be a unique skillset needed for effective instruction that goes beyond one's own educational background and understanding of mathematical content. This includes teaching behaviors such as using mathematical representations to build conceptual understanding for students, responsiveness to student questions and errors, accurately analyzing student work, and adapting instruction to support learning (Hill et al., 2005; Hill et al., 2008). As described by Hill et al. (2005), "Measuring quality *teachers* through performance on tests of basic verbal mathematics ability may overlook key elements in what produces quality *teaching*" (p. 375). Researchers have taken a deeper look into measuring teachers' MCK with a greater emphasis on examining teachers' *knowledge of how to effectively teach* a given academic subject. This concept traces back to research by Lee Shulman and colleagues in the 1980s, who coined the term "pedagogical content knowledge" (Shulman, 1986; Wilson et al., 1987). Shulman (1986) describes this type of knowledge as going beyond strong content-area knowledge to include knowledge needed for successful teaching (i.e., the ability to teach subject-matter knowledge to others).

Approaches to Measuring MCK

A number of approaches have been taken to measure teachers' knowledge of how to effectively teach mathematics. One of the most widely used assessments is the Mathematical Knowledge for Teaching (MKT; Hill et al., 2004), administered in a range of studies (Agodini & Harris, 2016; Campbell et al., 2014; Hill et al., 2005; Jacob et al., 2017; Santagata et al., 2011; Stein & Kaufman, 2010). Hill et al. (2004) use the term "specialized knowledge of content" to describe the items targeting the unique knowledge needed for teaching mathematics, which they define as "building or examining alternative representations, providing explanations, and evaluating unconventional student methods" (p. 16). For example, on one assessment item, teachers are asked to examine three hypothetical student work samples and identify which ones indicate a similar mathematical error for adding one- and two-digit numbers using the standard algorithm for addition. On another item, teachers are asked to select the most instructionally relevant list of decimals that a hypothetical teacher would use during instruction to help students learn how to correctly order decimals from smallest to largest. Items on the MKT also assess for mathematics subject-matter knowledge that would be known to someone with a background in mathematics but are not specific to teaching mathematics. Other measures used in research to capture MCK include items taken from the Mathematics Professional Development Institutes (Santagata et al., 2011), other researcher-developed assessments (Dash et al., 2012; Tchoshanov et al., 2008; Wilkins, 2008), or single-item proxies of MCK such as a question on the NAEP assessment (Telese, 2012).

Associations between Teacher MCK and Student Achievement

Examinations of teacher MCK have revealed a number of critical findings. After controlling for student- and teacher-level covariates, teacher MCK was a significant predictor of student mathematics achievement gains across the academic year for students in the early and late elementary grades (Campbell et al., 2014; Hill et al., 2005). Additionally, teacher MCK significantly predicted student mathematics achievement gains above and beyond other variables such as mathematics courses taken or years of experience teaching (Hill et al., 2005). Hill et al. (2005) examined whether the relation between MCK and student mathematics achievement was constant across the range of teacher content knowledge scores. Interestingly, the researchers found that students of teachers who scored in the lower third of the distribution of MCK made significantly less progress in mathematics compared to their peers with more knowledgeable teachers;

however, there was no association for teachers scoring above this threshold on the knowledge measure.

Using a researcher-developed measure for middle school teachers, the Teacher Content Knowledge Survey, Tchoshanov (2011) examined three different types of teacher MCK, including knowledge of facts and procedures, knowledge of concepts and connections, and knowledge of models and generalizations. The researcher found that only knowledge of concepts and connections (e.g., making connections between concepts, using multiple mathematics representations) significantly predicted student mathematics achievement in a sample of middle school teachers. Interestingly, the other types of teacher knowledge were not associated with student mathematics achievement. These other knowledge types focused on teachers' knowledge of facts (e.g., the rule of fraction division) and knowledge of models (e.g., generalization of mathematical statements or proving theorems).

Using teacher subject-matter tests in mathematics and reading and a national evaluation of sixth grade students' mathematics achievement, Metzler & Woessman (2012) found that a one standard deviation increase in teacher MCK was associated with an increase in student mathematics achievement by 9% of a standard deviation. Interestingly, the researchers did not find a significant association between teacher content knowledge in reading and student reading achievement, pointing to a potentially unique role of content knowledge in mathematics.

Outcomes of Content-focused Mathematics PD Evaluations

Given associations between teacher MCK and student mathematics achievement, systematic efforts have been carried out to investigate the impact of content-focused teacher PD programs on teachers' MCK, instructional behaviors, and student mathematics achievement (Dash et al., 2012; Harris & Sass, 2011; Jacob et al., 2017; Garet et al., 2008; Garet et al., 2010, 2011; Garet et al., 2016; Sample McMeeking et al., 2012). These PD initiatives have spanned grade level and mathematical content, typically lasting for multiple days within a year with some programs extending across multiple years. For example, Garet et al. (2010, 2011) implemented a two-year, 114-hour teacher PD program focused on building teachers' conceptual knowledge of rational numbers, including having teachers solve problems, explain concepts and procedures, and use visual representations during instruction. Garet et al. (2016) investigated an 80-hour teacher PD program, Intel Math, focused on building teachers' knowledge of K-8 mathematics. Jacob et al. (2017) implemented a week-long summer PD program with follow-up in-service days for fourth and fifth grade teachers focused on building their mathematical knowledge for teaching. Dash et al. (2012) carried out a 70-hour online PD program targeted at increasing teachers' pedagogical content knowledge of rational number concepts.

The majority of these programs led to increases in teacher MCK compared to a business-as-usual (BAU) control condition (for an exception, see Garet et al., 2010, 2011). Additionally, studies that included a comparison of teachers' instructional behaviors following the PD found a few key improvements, such as teachers eliciting student thinking more frequently (Garet et al., 2010) and using a greater quantity and quality of mathematical explanations during instruction (Garet et al., 2016). It should be noted, however, that no differences were found in the rates of several other instructional behaviors, such as teachers' use of incorrect or imprecise mathematics, teachers' use of mathematical representations, and teachers' focus on mathematical reasoning (Garet et al, 2010; Garet et al., 2016).

Despite most content-focused teacher PD programs increasing teacher MCK and resulting in some improvements in teachers' instructional behaviors, the evidence that these types of PD programs effect change at the student level is extremely limited. Gersten and colleagues (2014) conducted a systematic literature review of mathematics PD evaluations and their impact on student mathematics achievement. After finding 32 studies with an acceptable research design, the researchers found that only two studies demonstrated a positive impact on student mathematics achievement (i.e., Perry & Lewis, 2011; Sample McMeeking et al., 2012). Of these two programs, only one focused on building teachers' MCK (i.e., Sample McMeeking et al., 2012), with the other study focused on teacher collaboration through lesson study groups. Sample McMeeking et al. (2012) used a quasi-experimental design, where teachers self-selected into the PD condition, and therefore may have been more motivated to improve their instructional practices, or may have entered the study with better teaching practices. In light of the billions of federal dollars dedicated to content-focused PD programs, along with the school resources and teacher time spent on these efforts, these findings are extremely disappointing.

The Role of High-quality Curricula

While limited research indicates that intervening on teacher MCK increases student mathematics achievement, the use of high-quality core curricula has a higher level of evidence for increasing mathematics achievement, particularly for programs that include built-in teacher supports (Agodini et al., 2009; Gersten, Beckmann, et al., 2009).

For example, Agodini et al. (2009) led a large-scale evaluation of four commonly-used first grade core curricula (*Investigations*, *Math Expressions*, *Saxon*, and *Scott Foresman-Addison Wesley Mathematics*) aligned with different pedagogical approaches. After randomly assigning schools in participating districts to one of the four curricula, the researchers found that the two curricula relying primarily on teacher-directed or blended instruction (*Math Expressions* and *Saxon*) resulted in greater student mathematics achievement gains across the school year compared to other curricula that adopted more student-directed or non-explicit approaches.

Though teachers' use and implementation of curricula can vary, high-quality curricula may help teachers, even those with limited training in mathematics, employ effective instructional techniques (Stein et al., 2007). For example, curricula that provide guidance about how to enact lessons, intended use of materials, and specific language to use during instruction are associated with greater gains in student mathematics achievement compared to curricula that provide minimal descriptions of teacher language and actions (Remillard et al., 2014). These more effective curricula are often fully or partially scripted, providing teachers with precise and consistent mathematical language to use across lessons (Remillard & Reinke, 2012).

Another key feature of strong mathematics curricula includes the use of visual representations to build conceptual understanding (Owens & Fuchs, 2002; Witzel et al., 2003). Curricula often include different types of mathematical representations to teach abstract concepts, including number lines, place value charts, or manipulatives such as base ten blocks (Gersten, Beckmann, et al., 2009). Effective curricula specify how teachers should use and gradually scaffold these models, beginning with concrete models (e.g., using manipulative counters to model counting on in addition), transitioning to representational models (e.g., counting on using a number line), and finally moving to abstract models (e.g., counting on verbally without a model; Agrawal & Morin, 2016; Gersten, Beckmann, et al., 2009).

High-quality curricula also specify a range and sequence of mathematical examples (Carnine et al., 1997; Witzel et al., 2003), which can reduce the burden of developing original examples for the teacher. These types of supports can allow teachers to focus on in-the-moment instructional modifications, such as dealing with challenging student behaviors or providing corrective feedback when students make an error.

MCK, Curriculum, and Student Mathematics Achievement

As stated previously, curricula provide varying degrees of support for implementation (Remillard et al., 2014; Stein & Kaufman, 2010). Curricula that provide a high level of support to teachers, such as those that include specific teacher language or explanations of how to effectively use mathematical representations, may reduce the impact of MCK on teaching behaviors and student outcomes. To date, two studies have investigated relations among teacher MCK and curriculum.

The first study, conducted Stein and Kaufman (2010), examined two widely-used mathematics curricula, *Investigations* and *Everyday Mathematics*. Upon examination of teacher supports in each curriculum, the researchers determined that *Investigations* provided greater implementation support due to it providing a rationale for how specific mathematics tasks should be taught and providing anticipation for how students might respond to mathematics tasks (found in 80% and 91% of *Investigations* lessons, compared to 21% and 28% of *Everyday Mathematics* lessons). The researchers conducted observations in two large districts that had each newly adopted one of the two programs and found that teachers using *Investigations* had a higher quality of implementation overall. Using the MKT, the researchers also examined correlations between teacher MCK and implementation quality. They found that teacher MCK was significantly associated with implementation quality for teachers using *Everyday Mathematics*, but did not find significant associations for teachers using *Investigations*. This is possibly due to *Investigations* providing a higher degree of teacher support, resulting in teachers' MCK being less related to their implementation of the curriculum. One major limitation of this study is that because all teachers within a district used the same curriculum, there may have been systematic differences within districts that led to differential implementation of curricula. Additionally, the researchers' focus was solely on the relation between curriculum and instruction, and did not investigate the impact on student mathematics learning.

The second study used data collected from the large scale evaluation of four early elementary mathematics curricula (*Investigations*, *Math Expressions*, *Saxon*, and *Scott Foresman-Addison Wesley Mathematics*; Agodini et al., 2009). Agodini and Harris (2016) investigated whether teachers' MCK moderated curriculum effects, comparing two curricula at a time and using the MKT to measure teacher MCK. The researchers used hierarchical linear models (HLMs), with student mathematics achievement as the outcome variable, to account for nesting of the data. To detect moderation, the researchers examined curriculum effects for teachers at the average level of MCK and for teachers scoring one standard deviation above the mean. The researchers found that teacher MCK significantly moderated curriculum effects when comparing the two curricula previously demonstrated to produce the greatest gains in student mathematics achievement (*Saxon* and *Math Expressions*) to *Investigations*. Specifically, the effect of *Investigations* was similar to *Saxon* and *Math Expressions* for teachers with average MCK, but *Investigations* was less effective than the other programs for teachers with MCK one standard deviation above the mean, with effect sizes ranging from -.13 to -.16. The researchers interpreted this finding as *Saxon* and *Math Expressions* being more robust across levels of teacher MCK compared to *Investigations*, where the effectiveness of the curriculum was more impacted by teacher MCK. While the researchers examined teacher MCK as a moderator of curriculum effects, they did not examine whether the relation of teacher MCK and student mathematics achievement varied depending on the curriculum used.

Study Purpose and Research Questions

Though mathematics PD programs frequently target teacher MCK, there is mixed evidence of the association between teacher MCK and student mathematics achievement. Additionally, with the exception of one study (Sample McMeeking et al., 2012), efforts to intervene on teacher MCK have not demonstrated a substantial impact on student mathematics achievement (Dash et al., 2012; Jacob et al., 2017; Garet et al. 2016). On the contrary, an abundance of research indicates that the use of high-quality curricula is associated with higher student mathematics achievement (e.g., Agodini et al., 2009; Remillard et al., 2014). It is possible that curricula with a high level of teacher support can lead teachers to effectively teach mathematics, regardless of their level of MCK. This hypothesis is supported by research indicating that high-quality curricula are more robust across variations in teachers' MCK (Agodini & Harris, 2016; Stein & Kaufman, 2010).

The current study builds on prior research to investigate whether the relation between teacher MCK and positive classroom outcomes (i.e., effective instructional behaviors and student mathematics achievement gains) varies based on the curriculum used.

This study draws from a large scale research study (Clarke et al., 2011; Clarke et al., 2015) focused on examining the efficacy of Early Learning in Mathematics (ELM), a core kindergarten curriculum, compared to BAU, district-approved curricula. ELM uses an explicit instructional design and provides built-in teacher supports within each lesson. It has been shown to be particularly effective for students at-risk in mathematics (Clarke et al., 2011; Clarke et al., 2015). While overall differences in student mathematics achievement gains across the kindergarten year between students in the ELM and control conditions have not been documented, when examining students in the ELM and control conditions classified as at-risk (approximately 66% of the sample in Clarke et al., 2011, and 50% of students in Clarke et al., 2015), students receiving ELM made greater gains across their kindergarten year compared to students in the control condition, and made greater gains toward catching up to their typically-achieving peers. For example, Clarke et al. (2011) found that on an early numeracy measure, at-risk students receiving ELM gained 20.6 points on their typically-achieving peers, whereas at-risk students receiving BAU curricula gained only 9.6 points. Using data from the ELM efficacy study, the current study will investigate two related research questions:

(RQ1) Does curriculum (ELM vs. BAU) moderate the association between teacher MCK and instructional behaviors?

Research indicates that teacher MCK is positively associated with teaching behaviors (Garet et al., 2010, 2011; Garet et al., 2016; Hill et al., 2008). Research also indicates that curricula adopting a teacher-directed or blended approach are associated with higher rates of effective instructional behaviors, such as teachers posing more individual response opportunities during instruction (Doabler et al., 2015). Thus, it was hypothesized that teacher MCK would predict teachers' instructional behaviors for teachers using a BAU core curriculum that varied in the degree of teacher support provided. For teachers using ELM, it was hypothesized that these associations would be weaker given that ELM includes built-in supports that may have guided teachers to enact effective instructional behaviors, regardless of their MCK. The specific instructional behaviors examined included teacher demonstrations, group response opportunities, and individual response opportunities. These behaviors were selected due to research indicating their association with student mathematics achievement (Doabler et al., 2015; Clements et al., 2013) and with effective instructional practices more broadly (Archer & Hughes, 2011). This question was examined using a continuous and binary indicator (lowest three quartiles versus upper quartile) of teacher MCK, given research indicating that associations differ based on how MCK is defined or distributed (Agodini & Harris, 2016).

(RQ2) Does curriculum (ELM vs. BAU) moderate the association between teacher MCK and student mathematics achievement gains in kindergarten?

It was hypothesized that in BAU classrooms, teachers' MCK would predict student mathematics achievement gains given research indicating positive associations between these variables (e.g., Hill et al., 2005). It was hypothesized that these associations would be weaker in ELM classrooms given that ELM provides a high degree of support to teachers and therefore would reduce the effect of MCK on student outcomes. Consistent with the first research question, this question was examined using both continuous and binary indicators of teacher MCK.

CHAPTER II: METHOD

Design

The ELM large-scale efficacy trial (Clarke et al., 2015) was conducted in school districts in Oregon (2008-2009) and Texas (2009-2010; for detailed description of methods, see Clarke et al., 2015). This project utilized a group-randomized control trial design (Murray, 1998) to investigate the efficacy of the ELM core kindergarten curriculum, with mathematics achievement data collected from individual students and teacher data (survey data and observations) collected from each classroom. Thus, the primary analysis framework was multilevel models that nested students within classrooms, the unit of randomization to condition. Kindergarten classrooms (n = 129) were randomly assigned to receive the ELM curriculum (n = 68) or BAU mathematics instruction (n = 61), blocking on school. The sample was approximately evenly split between Oregon (n = 64) and Texas (n = 65) classrooms. Classrooms were matched based on half-day (n = 17) or full-day (n = 112) schedules.

Participants

Schools

The 46 participating schools in Oregon and Texas included public (n = 32), private (n = 11), and charter (n = 3) schools in urban and suburban areas (see Table 1 for demographic information regarding schools and teachers). Schools and teachers received a stipend for study participation. Teachers in the ELM condition received professional development for implementation of ELM and compensation for attending outside training. Teachers in the control condition received access to the ELM curriculum at the end of the study.

Table 1

Descriptive Statistics for Classrooms and Teachers by Condition (ELM vs Control)

	ELM	Control	Total
Number of classrooms	68 (53%)	61 (47%)	129
Teacher gender			
Female	65 (51%)	62 (49%)	127 (98%)
Teacher ethnicity			
White	50	42	92
Hispanic	11	11	22
African American	5	6	11
Native American	0	1	1
Asian American	1	0	1
Teacher education			
Master's degree	28	21	49
Completed 3 or more math courses	18	12	6
Taught kindergarten for 4+ years	39	35	73

Teachers

Participating kindergarten teachers (*n* = 130) taught the 129 classrooms (two teachers each taught a half-day in a single classroom). Of the 130 teachers, 127 (98%) were female. Teacher-reported demographics indicated that 92 (71%) were White, 22 (17 %) were Hispanic, 11 (8%) were African American, one (<1%) was Native American, one (<1%) was Asian American, and three (2%) did not report demographic information. Regarding teacher-reported credentials and teaching background, forty-nine teachers (38%) held a master's degree, 30 (23%) completed three or more college math courses, 68 (52%) completed college algebra, and 72 (56%) had taught kindergarten for four or more years. Twenty-four teachers (19%) reported spending 21 – 40 minutes per day on mathematics, 45 (35%) reported 41 – 60 minutes per day, and 37 (29%) reported 61 or more minutes per day.

Students

The full sample of students included 2,598 kindergarteners in ELM (*n* = 1,401) and control (*n* = 1,197) classrooms (see Table 2 for student demographic information). Of the full sample of students, 120 (5%) were eligible for special education services, and 708 (27%) were identified as ELs. District-provided demographic data was only available for students who attended public schools, comprising 61% of the sample. Of the students with demographic data, approximately 76% of the student population qualified for free or reduced-price lunch programs. Across Oregon and Texas, 909 (57%) students were White, 265 (17%) were African American, 218 (14%) were American Indian/Alaska Native, 136 (9%) were Asian, 11 (<1%) were Native Hawaiian or Islander, and 43 (3%) were multiple races.

Table 2

Descriptive Statistics for Students by Condition (n = 2,598)

	ELM	Control	Total
Student demographics			
Age in months at T1 *M (SD)*	67.06 (4.07)	67.22 (4.05)	
# Eligible for SPED	64 (5%)	56 (5%)	120
# ELs	407 (29%)	301 (25%)	708
Student race/ethnicity			
White	494 (35%)	415 (35%)	909
African American	126 (9%)	139 (12%)	265
American Indian/Alaskan Native	113 (8%)	105 (9%)	218
Asian	72 (5%)	64 (5%)	136
Native Hawaiian or Islander	7 (0.5%)	4 (0.3%)	11
Multiple races	22 (2%)	21 (2%)	43
Data unavailable	567 (41%)	449 (38%)	1,016
Total students	1,401 (54%)	1,197 (46%)	2,598

ELM Curriculum

ELM is a 120-lesson, core kindergarten curriculum, designed for whole-class instruction and focused on building foundational early mathematics concepts. Each lesson consists of a 15-minute daily calendar routine, as well as a 45-minute mathematics lesson. Each lesson includes four to five activities, allowing for lessons to be organized in tracks with skills introduced, built upon, and frequently reviewed over time to allow for mastery and retention. Each ELM lesson includes a cumulative Math Practice worksheet with a “Note Home” in English and Spanish to encourage parent involvement and additional at-home practice. The curriculum was designed to support a wide range of learners, with a particular focus on supporting students entering kindergarten at-risk in mathematics, through two key elements: (a) focusing on the most critical content for students to learn in kindergarten, and (b) using research-based instructional design principles including built-in teacher supports.

Critical Content

The curriculum covers content across three math strands: numbers & operations, geometry, and measurement. Every fifth lesson is focused on problem-solving which incorporates skills across strands and encourages students to think critically about previously-learned concepts. Content was selected based on the National Council of Teachers of Mathematics Focal Points for kindergarten (NCTM, 2006) and other recommended guidelines for early mathematics curricula (NMAP, 2008), and aligns with the CCSS-M (2010; see Appendix A). The program’s scope maintains a narrow focus to ensure mastery of critical mathematics skills, with greater emphasis placed on the development of whole number understanding compared to the other two strands (NCTM, 2006; NMAP, 2008). Quarterly in-program assessments are built into the curriculum for teachers to assess the progress of individual students and the class as a whole. In addition to the three content strands, a strong focus is placed on teaching mathematics vocabulary to ensure that students with less exposure to mathematics prior to entering kindergarten and ELs without exposure to subject-matter vocabulary are provided an equal opportunity to learn. The curriculum guides teachers to explicitly and systematically introduce new vocabulary words, providing examples and non-examples, with students then using the words in the context of lessons.

Instructional Design Principles and Teacher Supports

ELM uses an explicit and systematic instructional design (Gersten, Chard, et al., 2009) to create high-quality instructional interactions between teachers and students (Clarke et al., 2015). Embedded in the curriculum design are teacher supports to assist teachers in effectively delivering the curriculum. For example, each quarter of ELM includes a Teacher's Guide that outlines the scope and sequence of critical content taught across the quarter. A "Teacher Note" is included before each set of five lessons to outline lesson objectives and to alert teachers to potential difficulties students may encounter with new content. Detailed teacher instructions and suggested scripting are used to provide descriptions of lesson activities, provide consistent and precise mathematical language, and to highlight key vocabulary words and definitions. ELM also uses teacher scripting to help teachers effectively scaffold instruction. For example, when introducing a new concept, teachers provide clear demonstrations while maintaining student attention by posing scripted questions or having students repeat a vocabulary word or describe a mathematical concept. Next, teachers guide students to practice mathematics skills as a group with a greater degree of student participation. Last, teachers have students practice mathematics skills independently while providing confirmative or corrective feedback. This sequence occurs within and across lessons, giving students repeated exposure to challenging mathematical concepts across time.

ELM also relies upon the concrete-representational-abstract (CRA) sequence to build deep understanding of complex mathematical concepts (Agrawal & Morin, 2016; Witzel et al., 2003). For example, students are first introduced to new mathematical concepts using manipulatives, such as using teddy bear counters or finger models to represent numbers. Next, students are introduced to a visual models representing the same concept, such as a number line or ten frame. Last, students are guided to work with the abstract representation, such as using numerals to represent numbers. The CRA sequence is outlined for teachers in lesson scripting and detailed information about program materials. Along with developing understanding of mathematical concepts, ELM places emphasis on developing procedural fluency and automaticity to help students master mathematics concepts and skills. Students receive ample practice on skills over time, leading to increased exposure to mathematical concepts and fostering automaticity. Additional student practice opportunities are built into the end of every lesson through student completion of the independent Math Practice worksheet.

BAU Curricula

The most commonly-used curricula by classrooms in the control condition were published by McGraw Hill (*Texas Mathematics* or *Everyday Mathematics*, $n = 21$; see Table 3 for a complete list of programs and publishers used in Oregon and Texas). Other commonly used programs included *Harcourt Math* ($n = 15$), *Scott Foresman-Addison Wesley Mathematics* ($n = 7$), *Progress in Mathematics* ($n = 3$), and *Investigations in Number, Data, and Space* ($n = 2$). Four teachers indicated that they did not use a curriculum or used teacher-made materials, and seven teachers did not provide a response to the survey item.

The pedagogical approaches and level of teacher supports varied across the published curricula used in the control condition. The most commonly-used BAU program, *Everyday Mathematics*, has been described as having an "inquiry approach to mathematics, in which students are expected to develop mathematical thinking through the exploration and application of mathematical principles rather than through direct instruction" (p. 3, Nelson et al., 2007). *Everyday Mathematics* has also been described as a "low-support curriculum" (p. 667, Stein & Kaufman, 2010), where teachers are provided with limited support for anticipating student responses and for understanding lesson rationales (Stein & Kim, 2009). Similar to *Everyday Mathematics*, *Investigations in Number, Data, and Space* has been described as having a student-centered approach (Agodini et al., 2009; Remillard et al., 2014) but has been classified as a "high-support curriculum" (p. 667, Stein & Kaufman, 2010; Stein & Kim, 2009), providing a higher degree of implementation support to teachers.

Harcourt Math and *Scott Foresman-Addison Wesley Mathematics* are viewed as teacher-directed, or explicit in nature (Agodini et al., 2009; Nelson et al., 2007). Both programs rely upon student worksheets as the primary mode of instruction. *Scott Foresman-Addison Wesley Mathematics* is characterized as providing minimal support to teachers, without the provision of explicit scripts or guidance of teacher actions (Remillard et al., 2014). *Harcourt Math* largely relies upon whole-class instruction and practice in the form of student worksheets, with little support for teachers to differentiate instruction for students beyond providing alternative worksheets (Nelson et al., 2007).

Table 3

Curricula Used by Control Classrooms in Oregon and Texas

Program (Publisher)	Oregon	Texas	Total (%)
Texas Math, Everyday Mathematics (McGraw Hill)	2	19	21 (34%)
Harcourt Math (Houghton Mifflin Harcourt)	14	1	15 (26%)
Scott Foresman-Addison Wesley Mathematics (Pearson)	7	0	7 (11%)
Progress in Mathematics (Sadlier)	0	3	3 (5%)
Investigations in Number, Data, and Space (Pearson)	2	0	2 (3%)
Other published curriculum	0	2	2 (3%)
No curriculum or teacher-made materials	1	3	4 (7%)
Did not indicate	4	3	7 (11%)

Measures

Test of Early Mathematics Achievement, Third Edition (TEMA-3; Ginsburg & Baroody, 2003)

The TEMA-3 is an individually administered, norm-referenced assessment, intended for use with children ages three to eight. It is designed to measure informal and formal mathematics skills, and takes approximately 30-40 minutes to administer. The TEMA-3 includes a range of items sampling across skills in the domains of numbering (reading, writing, and representing numbers), comparing numbers, number facts, calculation skills, and understanding of mathematical concepts. The TEMA-3 has good psychometric properties, with high internal reliability (coefficient alphas range from .94

to .96), high test-retest reliability (ranging from .82 to .93), and moderate criterion-related validity with other measures of early mathematics skills (.54 to .91; Ginsburg & Baroody, 2003). Of the available student mathematics achievement measures in the ELM efficacy trial, the TEMA-3 was used in this study due to its focus on assessing for students' conceptual understanding of mathematics and its sensitivity to students scoring at the lower end of the distribution. TEMA-3 raw score gains (calculated by subtracting students' raw score from the fall administration from their raw score in the spring) were used as the measure of student mathematics achievement. Raw scores were chosen for ease of interpretation, and previous research using this data set found that results of analyses using other types of scores (e.g., standard scores, percentile ranks) were minimally different and resulted in the same pattern of findings (Clarke et al., 2015).

Mathematical Knowledge for Teaching (MKT; Hill et al., 2004)

The MKT survey administered in the ELM efficacy trial consisted of 24 untimed multiple-choice items selected from Hill et al. (2004)'s MKT measure. Completion time was approximately 20 to 30 minutes, with content covering mathematics from kindergarten to sixth grade, and spanning the domains of number and operations, place value, geometry, and algebra. Items were designed to assess for teachers' mathematics subject-matter knowledge and pedagogical content knowledge. For example, one subject-matter knowledge item asked teachers to respond to the statement, "Multiplication makes numbers larger." Multiple-choice responses included "True for all numbers", "Not always true", and "I'm not sure". An item designed to measure teachers' pedagogical content knowledge included viewing a hypothetical student's work putting decimals in order, and indicating the error(s) made. Responses included "They are ignoring place value”, “They are ignoring the decimal place”, “They are guessing”, “They have forgotten their numbers between 0 and 1”, or “They are making all of the above errors”. Reliabilities of the MKT range from .86 to .95. The number and operations and algebra scales correlate at .76 (Hill et al., 2004). In the current study, teacher MKT scores were reported as the percentage correct out of the 24 multiple-choice items.

Classroom Observation of Student-Teacher Interactions–Mathematics (COSTI-M; Doabler et al., 2015)

The COSTI-M observation system is a modified version of a reading instruction observation system (Smolkowski & Gunn, 2012) designed for mathematics. Observers collect frequency counts of teachers’ instructional behaviors across an observation period, with the rate of instructional behaviors calculated by dividing the total number of instructional interactions by the total duration of the observation. In the current study, the following instructional behaviors were analyzed: (a) teacher demonstrations, (b) group response opportunities, and (c) individual response opportunities. Teacher demonstrations were defined as instances that a teacher provided a clear mathematical explanation, verbalized mathematical thought processes, or employed a physical demonstration of a mathematical concept. Group response opportunities were defined as math verbalizations from two or more students. Individual response opportunities were defined as one student verbalizing or providing a physical demonstration of mathematical understanding. Previous investigations of the COSTI-M using the ELM data set have demonstrated stability intraclass correlation coefficients (ICCs) ranging from .26 to .44, with modest average stability of rates of instructional behaviors (.45 to .65; Doabler et al., 2018).

Using the ELM dataset, Doabler et al. (2015) found high interobserver agreement, with ICCs ranging from .67 to .95.

Study Procedures

Data Collection

Teacher surveys, including teacher demographics and the MKT measure, were completed by all participating teachers (ELM and control teachers) in October of 2009 (Oregon) and 2010 (Texas), prior to the implementation of ELM. Student mathematics achievement measures were collected in the fall prior to implementation of ELM, and in the spring after ELM classrooms completed the program. Student measures were administered by trained staff who met a reliability standard of at least .85 prior to collecting data in schools and again during an in-school shadow-coding session. Data collector training ranged from 4-6 hours in the fall and again in the spring prior to post-testing.

Classroom Observations

Observers underwent an additional 11+ hours of training focused on the COSTI-M and other observation measures that included lecture, video practice, a video reliability check, and a real-time reliability check in a classroom where observers were required to meet a reliability standard of .80. Booster sessions were provided prior to each additional observation. In each ELM and control classroom, an observation was conducted in the fall, winter, and spring, each approximately six weeks apart. Out of 379 scheduled observations, only eight (2%) were not completed due to teacher absences or scheduling conflicts. Observations lasted between 30 and 90 minutes, for the duration of mathematics instruction.

Professional Development

All participating teachers in ELM and control classrooms met briefly to discuss project logistics and to complete demographic surveys. ELM teachers participated in three four-hour trainings conducted across the school year focused on curriculum implementation. Trainings were led by the lead curriculum author and/or project coordinator. Trainings focused on lesson content, classroom management, and implementing the ELM curriculum with fidelity. Teachers had the opportunity to practice teaching ELM lessons during the training and received feedback from trainers on teacher demonstrations, guided practice, and facilitating group and individual response opportunities.

Analytic Methods

For RQ1, the dependent variable was teacher instructional behaviors as measured by the COSTI, including (a) teacher demonstrations, (b) group response opportunities, and (c) individual response opportunities. For RQ2, the dependent variable was kindergarten student mathematics achievement gains on the TEMA-3. The independent variable for both RQ1 and RQ2 was teacher MCK, as measured by the MKT (Hill et al., 2004). Curriculum (ELM vs. BAU) was examined as a moderating variable for both research questions.

For tests of teacher-level moderation effects with a relatively small teacher sample size, the tradeoff between Type I and Type II errors represents a delicate balance. False conclusions about significant interaction effects (Type I errors) are problematic, as is failing to detect interaction effects (Type II errors). To balance the likelihood of the two types of errors, Cohen (1990) and Rosnow and Rosenthal (1989) recommend an adjustment to alpha, the Type I error rate. Thus, alpha was set to .10 for tests of main effects, interaction effects and for follow-up subgroup analyses in the presence of a significant interaction. With a sample of approximately 64 teachers per condition, there is power (.80) to detect correlations > .31 between MCK and teacher outcomes within the ELM and BAU conditions (Faul et al., 2007). Analysis procedures specific to each RQ are described below.

RQ1

The purpose of RQ1 was to investigate whether the association between teacher MCK and teacher instructional behaviors varied between teachers of ELM and teachers of BAU curricula. Pearson's *r* bivariate correlations were estimated among teacher MCK, teacher characteristics, and instructional behaviors. Multiple regression models were specified to regress instructional behaviors on Teacher MCK, Condition, and the MCK × Condition interaction, as specified by the following equation:

$$Y = b_0 + b_1 MCK + b_2 Condition + b_3 (MCK \times Condition) + e$$

where Y = the raw score on the teaching behavior variable and b_0, b_1, b_2, and b_3 are the intercept and regression coefficients associated with Teacher MCK, Condition, and the MCK × Condition interaction. Teacher MCK was centered to allow for interpretation of the intercept as the average instructional behavior for a teacher with average MCK (MCK = 0) in the BAU condition (Condition = 0). Separate models were analyzed for each instructional behavior, with predictor variables entered into the regression models simultaneously. Specifically, Model 1 included the effect of Teacher MCK, Condition, and the interaction between the two. If the interaction term was not significant then Model 2 was respecified to exclude the interaction term. If the interaction was statistically significant, then simple slope analyses were performed within each study condition. A significant interaction indicated that the effect of Teacher MCK on a given instructional behavior (i.e., rate of teacher demonstrations, group response opportunities, or individual response opportunities) varied by condition. After examining Teacher MCK continuously, Teacher MCK was dichotomized by comparing teachers in the lowest three quartiles of MCK to teachers in the upper quartile of teacher MCK, in alignment with previous research on the interaction between teacher MCK and curriculum (e.g., Agodini & Harris, 2016). All regression models were computed using SPSS (IBM Corp, 2016).

RQ1 Model Assumptions

Assumptions of linear regression were examined across all models. Distributions of teacher MCK and teacher demonstrations were approximately normal. Distributions of the group responses opportunities and individual response opportunities were slightly positively skewed. Examination of skewness and kurtosis revealed that values were generally within the recommended bounds of -2 to 2 (Pedhazer, 1997). To test the assumption of normality, distributions of errors (i.e., unstandardized residuals) were examined using normal probability plots and had approximate alignment with the diagonal. To test the assumption of homoscedasticity, standardized residuals and standardized predicted values were plotted together and had approximately equal scatter across values. There was no evidence of multicollinearity, as evidenced by tolerance values greater than 0.1 (Aiken & West, 1991; Cohen et al., 2003). Influential cases were examined using inspection of studentized deleted residuals above or below two standard deviations, leverage values above 0.09 (computed by taking 3 for a small sample size * the number of parameters $k = 4$, and dividing by $n = 127$; Cohen et al., 2003), and Cook's

Distance of greater than 1 (Cook & Weisberg, 1982). Four outlying data points in the distribution of individual response opportunities were retained for analyses given that they were in the realm of the expected range for instructional behaviors.

RQ2

The purpose of RQ2 was to investigate whether the association between teacher MCK and student mathematics achievement varied between teachers of ELM and teachers of BAU curricula. Given the nested nature of the student mathematics achievement data, with individual students receiving instruction within a given classroom, two-level HLMs were used to investigate the interaction of teacher MCK and condition on student mathematics achievement. School-level data was omitted as a third level of nesting because the primary foci of the study included teacher and classroom variables without taking school effects into account. The multilevel models regressed student mathematics achievement gains at Level 1 on classroom characteristics (Teacher MCK, Condition, and Teacher MCK x Condition) at Level 2:

Level-1 Model: $MATHGAINS_{ij} = \beta_{0j} + r_{ij}$

Level-2 Model: $\beta_{0j} = \gamma_{00} + \gamma_{01} * (MCK_j) + \gamma_{02} * (Condition_j) + \gamma_{03} * (MCK\ x\ Condition_j)$

$+ u_{0j}$

Mixed Model: $MATHGAINS_{ij} = \gamma_{00} + \gamma_{01} * MCKn_j + \gamma_{02} * Condition_j + \gamma_{03} * MCK\ x\ Condition_j + u_{0j} + r_{ij}$

All HLMs were computed using HLM 8.0 (Raudenbush et al., 2019). Prior to introducing the conditional multilevel models, the ICC was calculated to determine the proportion of total variance in students' mathematics achievement scores occurring between classrooms. Specifically, an unconditional random effects model was applied with student mathematics achievement gains as the outcome variable, and the ICC was calculated by taking the between classroom variance ($u_0 = 7.069$) divided by the total variance ($u_0 = 7.069 + r = 38.027$). With an ICC of $\rho = .157$, 15.70% of variance in student mathematics achievement scores was occurring between classrooms, indicating that multilevel modeling was an appropriate analytic approach.

Full information maximum likelihood estimation was used for all analyses and robust standard errors were reported. Similar to RQ1 analyses, teacher MCK was evaluated as a continuous, centered variable and as a dichotomous, uncentered variable (lower three quartiles vs. upper quartile) in separate analyses. Specifically, Model 1 included the effect of Teacher MCK, Condition (0 = BAU, 1 = ELM), and their interaction. Significant interaction terms indicated that the effect of Teacher MCK on student mathematics achievement gains varied by condition. For models without any evidence of moderation (i.e., the p value of the interaction term was $\geq .10$), Model 2 was respecified to exclude the interaction term and the main effects model was analyzed.

RQ2 Model Assumptions

Model assumptions were tested throughout the process of generating HLMs. Cook's Distance was used to determine if any outliers in the dataset were influential. Histograms and box plots of the distribution of student mathematics achievement were visually inspected and tested for normality using parameters of skewness and kurtosis. Additionally, Level 2 OLS intercept residuals were plotted and the mean, skewness, and kurtosis were examined. Homogeneity of variance was tested using visual inspection of the Level 1 OLS intercept residual plot, and inspection of the Level 2 empirical Bayes intercept residuals. Last, independence of residuals was tested using the Durbin-Watson statistic and is accounted for by using multilevel structuring of the data.

Comparisons of Baseline Differences and Missing Data

Baseline Equivalency Analyses

Baseline equivalency analyses were conducted to ensure that random assignment of classrooms to the ELM and control conditions resulted in equivalent groups on student and teacher pretest characteristics. Independent samples *t*-tests and chi square analyses were used to examine teacher and student data for baseline differences between the ELM and control conditions on demographic and key study variables. There were no differences between the average age in months of students assigned to the ELM (M = 67.06) and BAU (M = 67.22) conditions ($t(2413) = .95$, $p = .34$, 95% CI [-.17, .48]), and no difference in White versus non-White ethnicity between conditions (X^2 (5) = 4.45, p = .49). There was a difference in the proportion of ELs in the ELM (n = 407) and BAU (n = 301) conditions, (X^2 (1) = 4.96, $p < .05$). No differences were found on TEMA-3 pretest scores between students in the ELM and BAU conditions ($t(2156) = .827$, $p = .41$, 95% CI (-.50, 1.23)) (see Table 4).

Teacher data were examined to determine if there were any differences in key teacher variables between teachers assigned to the ELM and control conditions. Independent samples *t*-tests indicated no differences between condition on MKT scores ($t(125) = -1.39$, $p = .17$, 95% CI [-9.74, 1.70]), the number of college math courses taken ($t(125) = -.70$, $p = .48$, 95% CI [-.49, .23]), and the number of years teaching kindergarten ($t(125) = .35$, $p = .73$, 95% CI [.08, .24]).

Missing Data

Mathematics achievement gain scores on the TEMA-3 were available for 1,972 students (approximately 76% of the total sample). Given the rate of missing data, chi square and independent samples *t*-tests were conducted to determine whether key variables differed between students with and without available TEMA-3 gains scores. No differences were found in regards to gender ($X^2(1) > .009$, $p = .922$) or the number of half- and full-day absences ($t(588.10) = -1.12$, $p = .26$, 95% CI [-1.24, .34]). However, missing TEMA-3 gains scores were systematically related to classification as an EL ($X^2(1) = 82.96$, $p < .001$), non-White ethnicity ($X^2(5) = 118.58$, $p < .001$), and eligibility for special education services ($X^2(1) = 24.79$, $p < .001$), such that there was a higher proportion of students in each category for students with missing gain scores. Differences were also observed on TEMA-3 pretest scores between students with and without spring TEMA-3 data. Specifically, TEMA-3 pretest scores of students with missing data at the spring administration ($M = 15.28$, $SD = 8.76$) were significantly lower than students without missing data ($M = 20.32$, $SD = 10.30$; $t(250.22) = 7.54$, $p < .001$, 95% CI [3.72, 6.36]).

Two Oregon teachers (1.5%) in the control condition that did not complete any of the teacher survey measures were excluded from the analyses. Due to the nested nature of the data and the centrality of these variables to the research questions, their students were excluded from analyses as well.

Treatment of Missing Data

Because group comparisons indicated that missing TEMA-3 gain score data were systematically related to other variables, multiple imputation was used to estimate missing values. Multiple imputation has been shown to work better than other methods in educational research, such as maximum likelihood imputation, mean imputation, or regression imputation, when there is a high proportion of missing data and a large sample size (Cheema, 2014). Predictors of student-level missing data included TEMA pretest scores and dummy-coded demographic characteristics including EL status (0 = English speaker, 1 = English learner), ethnicity (0 = White, 1 = non-White), and special education eligibility (0 = not eligible, 1 = eligible). Intervention condition was omitted as an auxiliary variable due to its potential to bias results (Smolkowski et al., 2010). For each HLM, 100 datasets were imputed and their average was used to generate model parameters. A random seed value was specified to ensure that analyses were consistent across model runs.

CHAPTER III: RESULTS

(RQ1) Does curriculum (ELM vs. BAU) moderate the association between teacher MCK and instructional behaviors?

Bivariate Correlations

Descriptive statistics for study variables by condition are reported in Table 4. Pearson's r bivariate correlations among teacher characteristics and instructional behaviors are displayed in Table 5. Correlations ranged from -.11 to .47. Teacher MCK was significantly correlated with the number of college math courses ($r = .24$, $p = .007$), teacher demonstrations ($r = .19$, $p = .034$), and group response opportunities ($r = .29$, $p = .001$). Teacher MCK was not significantly correlated with individual response opportunities ($r = .13$, $p = .154$). Correlations were highest between teacher demonstrations and group response opportunities ($r = .47$, $p < .001$). Correlations were not significant between the number of college math courses taken and any of the instructional behaviors. The number of years teaching was not significantly correlated with any other variable.

Table 4

Descriptive Statistics of Key Variables for Students and Teachers by Condition

	ELM	Control
Teacher variables (pretest)		
MKT score (% correct)	51.41 (15.41)	47.39 (17.15)
Number of college math courses	1.94 (1.02)	1.81 (1.03)
Years teaching	3.76 (1.35)	3.85 (1.31)
Teacher variables (during ELM)		
Teacher demonstration rate/min	0.58 (.30)	0.52 (.31)
Group response rate/min	1.34 (.63)	0.77 (.62)
Individual response rate/min	0.65 (.38)	0.46 (.27)
Students variables		
TEMA-3 pretest raw score	19.70 (10.46)	20.06 (10.04)
TEMA-3 gain score	14.36 (.21)	13.38 (.21)

Table 5

Correlations Among Teacher Variables and Teaching Behaviors (n = 127)

	1.	2.	3.	4.	5.	6.
1. Teacher MCK (% correct)	–					
2. Years teaching	-.02	–				
3. Number of college math courses	.24**	.07	–			
4. Teacher demonstration rate/min	.19*	-.08	-.10	–		
5. Group response rate/min	.29**	-.03	.06	.47**	–	
6. Individual response rate/min	.13	.02	-.11	.08	.19*	–

Note. *$p < .05$, **$p < .01$

Multiple Regression Analyses

Teacher MCK was first examined as a continuous predictor, with regression model results displayed in Table 6. The Model 1 columns in Table 6 show that the MCK by condition interaction was not significant for two of the instructional behavior outcomes: teacher demonstrations ($p = .136$), and group response opportunities ($p = .793$). The interaction term was dropped from these model to examine the main effect of teacher MCK with condition retained as a covariate (see Table 6, Model 2).

For teacher demonstrations, the model accounted for 5.0% of the variance in teacher demonstration rate ($F(2, 124) = 3.27$, $p = .041$). There was a statistically significant positive linear relationship between teacher MCK and the rate of teacher demonstrations after controlling for condition ($b = 0.003$, $SE = 0.002$, $\beta = .17$, $p = .053$). Specifically, for a 10% increase in teacher MCK, the teacher demonstration rate increased by 0.03 demonstrations per minute. Teachers of ELM did not have significantly higher rates of teacher demonstrations than teachers of BAU curricula after controlling for MCK ($b = 0.071$, $SE = 0.051$, $\beta = .12$, $p = .167$).

For group response opportunities, the model accounted for 25.1% of the variance in the outcome ($F(2, 124) = 20.76$, $p < .001$). There was a statistically significant positive linear relationship between teacher MCK and group response opportunities after controlling for condition ($b = 0.010$, $SE = 0.003$, $\beta = .24$, $p = .003$). For a 10% increase in teacher MCK, the rate of group response opportunities increased by 0.10 responses per minute. Teachers of ELM had significantly higher rates of group response opportunities than teachers of BAU curricula after controlling for MCK ($b = 0.558$, $SE = 0.107$, $\beta = .41$, $p < .001$). Specifically, ELM teachers elicited an additional 0.56 group responses per minute compared teachers in control classrooms.

The interaction term for the rate of individual response opportunities was statistically significant ($b = 0.006$, $SE = 0.004$, $p = .086$), indicating that the association between teacher MCK and the rate of individual responses varied by condition. Overall, the model accounted for 11.3% of the variance in the rate of individual responses ($F(3, 123) = 5.22$, $p < .001$). Simple slopes analyses revealed that for teachers of ELM, the relationship between teacher MCK and individual response opportunities was positive and statistically significant ($b = 0.005$, $SE = .003$, $\beta = .25$, $p = .047$; see Figure 1). This indicates that for every 10% increase in teacher MCK, ELM teachers elicited an additional 0.05 individual response opportunities per minute. For teachers of BAU curricula, the relationship between teacher MCK and individual response opportunities was not statistically significant ($b = -0.001$, $SE = 0.003$, $\beta = -.05$, $p = .674$).

Table 6

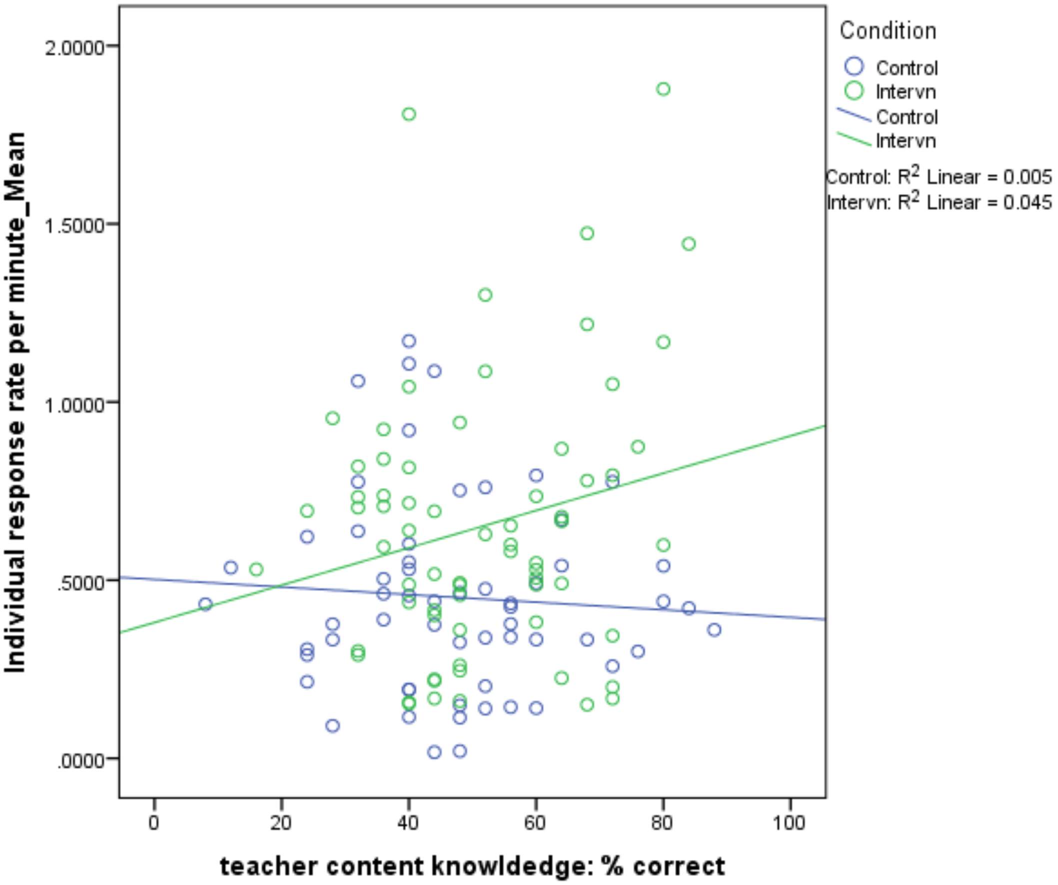
Results of Regressing Teachers' Instructional Behaviors on Teacher MCK as a Continuous Variable, Condition, and the Teacher MCK-by-Condition Interaction

	Teacher demonstration rate/min		Group response rate/min		Individual response rate/min
	Model 1	Model 2	Model 1	Model 2	Model 1
Intercept	0.509*** (0.37)	0.505*** (.037)	0.761*** (0.078)	0.759*** (0.078)	0.449*** (0.043)
Teacher MCK	0.005** (0.002)	0.003** (0.002)	0.011*** (0.005)	0.010*** (0.003)	-.001 (0.003)
Condition	0.071 (0.051)	0.071 (0.051)	0.558*** (0.107)	0.558*** (0.107)	0.191*** (0.059)
Teacher MCK * Condition	-0.005 (0.003)	–	-0.002 (0.007)	–	0.006* (0.004)
R^2	.067**	.050**	.251***	.251***	.113***
F	2.95**	3.27**	13.76***	20.76***	5.22***

Note. $^*p < .10$, $^{**}p < .05$, $^{***}p < .01$. Model 1 presents results from the moderation analyses. When interaction terms were not significant at the $p \leq .10$ level, the interaction term was excluded from the model to examine main effects of Teacher MCK and Condition (see Model 2). Standard Errors are reported in parentheses.

Figure 1

Interaction between Teacher MCK, Condition, and Individual Response Opportunities



Teacher MCK was next examined as a dichotomous variable, comparing teachers that scored in the lower three quartiles to teachers that scored in the upper quartile (0 = lower, 1 = upper; see Table 7). The interaction term for teacher demonstrations was significant (b = -0.250, SE = 0.126, p = .049), indicating that the association varied by condition between the lower three quartiles and upper quartile of teacher MCK and teacher demonstrations. Overall, the model accounted for 5.8% of the variance in the rate of teacher demonstrations (F(3, 123) = 2.52, p = .061). Decomposing the significant interaction revealed that for ELM teachers, the difference in teacher demonstration rate between the lower three quartiles and the upper quartile of teacher MCK was not statistically significant (*b* = -0.036, *SE* = 0.077, *d* = -.12 *p* = .639). For teachers using BAU curricula, there was a statistically significant positive difference in teacher demonstration rate between the lower three quartiles and the upper quartile of teacher MCK (*b* = 0.214, *SE* = 0.099, *d* = .71, *p* = .033). Thus, the effect of being a control teacher in the upper quartile of teacher MCK resulted in a 0.21 increase in the rate of teacher demonstrations compared to a control teacher in the lower three quartiles.

The interaction term was not statistically significant for group response opportunities (*p* = .179), or individual response opportunities (*p* = .208; see Table 7, Model 1), and thus the interaction term was dropped from the models to examine the main effects of teacher MCK and condition. For group response opportunities, the model accounted for 23.3% of the variance in the outcome (*F*(2, 124) = 18.88, *p* < .001). There was a statistically significant positive difference in the rate of group responses between the lower three quartiles and the upper quartile of teacher MCK after controlling for condition (*b* = 0.327, *SE* = 0.128, *d* = .52, *p* = .012). Specifically, the effect of being a teacher in the upper quartile of MCK compared to the lower three quartiles resulted in an increase of 0.33 in the rate of group response opportunities. ELM teachers had significantly higher rates of group response opportunities than control teachers, after controlling for level of teacher MCK (*b* = 0.563, *SE* = 0.108, *d* = .89, *p* < .001). Specifically, ELM teachers elicited an additional 0.56 group response opportunities per minute.

For individual response opportunities, the model accounted for 10.7% of the variance in individual response opportunities (*F*(2, 124) = 7.42, *p* = .001). There was a statistically significant positive difference in the rate of individual response opportunities between the lower three quartiles and upper quartile of teacher MCK after controlling for condition (*b* = 0.129, *SE* = 0.070, *d* = 0.34, *p* = .069), with teachers in the upper quartile eliciting an additional 0.13 individual response opportunities per minute. ELM teachers had significantly higher rates of individual response opportunities compared to control teachers, after controlling for level of teacher MCK (*b* = 0.185, *SE* = 0.059, *d* = 0.49, *p* = .002). Specifically, ELM teachers elicited an additional 0.19 individual response opportunities per minute.

(RQ2) Does curriculum (ELM vs. BAU) moderate the association between teacher MCK and student mathematics achievement gains?

Table 8 presents the results of the HLMs regressing student gains on the TEMA-3 across kindergarten on (a) teacher MCK as both a continuous and dichotomous predictor (lower three quartiles versus upper quartile), (b) condition (ELM vs. BAU), and (c) the interaction between the two. For both definitions of teacher MCK, the interaction term was not significant (*p* = .847 when examining MCK continuously, and *p* = .973 when examining MCK dichotomously; see Table 8, Model 1) and was therefore excluded from Model 2. Thus, interpretation focuses on Model 2, regressing student mathematics achievement gains on teacher MCK and condition.

First, examining teacher MCK as a continuous predictor, the average mathematics achievement gain score for students of control teachers with average teacher MCK was 15.41 (*SE* = 0.54, *p* < .001). For a one percentage point increase in teachers' MCK score, student gain scores decreased by -0.05 points (*SE* = 0.03, *p* = .033) after controlling for intervention condition. Compared to students of control teachers, students of ELM teachers had higher gain scores by 1.54 points (*SE* = 0.73, *p* = .038) after controlling for

Table 7

Results of Regressing Teachers' Instructional Behaviors on Teacher MCK as a Dichotomous Variable, Condition, and the Teacher MCK-by-Condition Interaction

	Teacher demonstration rate/min	Group response rate/min		Individual response rate/min	
	Model 1	Model 1	Model 2	Model 1	Model 2
Intercept	0.462 (0.041)***	0.644*** (0.086)	0.682*** (0.081)	0.449*** (0.047)	0.430*** (0.045)
Teacher MCK	0.214** (0.099)	0.548* (0.208)	0.327** (0.128)	0.015 (0.114)	0.129* (0.070)
Condition	0.130** (0.058)	0.638*** (0.121)	0.563*** (0.108)	0.146** (0.066)	0.185*** (0.059)
Teacher MCK * Condition	-0.250** (0.126)	-0.356 (0.264)	–	0.183 (0.145)	–
R^2	.058*	.245***	.233***	.118**	.107***
F	2.52*	13.28***	18.88***	5.51**	7.42***

Note. $*p < .10$, $**p < .05$, $***p < .01$. Model 1 presents results from the moderation analyses. When interaction terms were not significant at the $p \leq .10$ level, the interaction term was dropped from the model to examine main effects of Teacher MCK and Condition (see Model 2). Standard Errors are reported in parentheses. Teacher MCK was coded as 0 = lower three quartiles, 1 = upper quartile.

teacher MCK. Variance components indicated that 21.6% of the variance in student mathematics occurred between classrooms and that significant between classroom variation remained after accounting for teacher MCK and condition ($p < .001$).

Teacher MCK was next examined as a dichotomous predictor of student mathematics achievement. The average mathematics achievement gain score for students of control teachers in the lower three quartiles of MCK was 15.82 (*SE* = 0.56, $p < .001$). Having a teacher that scored in the upper quartile of MCK compared to the lower three quartiles of MCK resulted in a decrease in student mathematics achievement gains by 1.79 points (*SE* = 0.80, $p = .026$) after controlling for condition. Students of ELM teachers as compared to control teachers benefitted from a 1.52 increase in student mathematics achievement gains (*SE* = 0.72, $p = .036$) after controlling for teacher MCK. Variance components indicated that 21.8% of the variance in student mathematics achievement occurred between classrooms and that significant between classroom variation remained after accounting for teacher MCK and condition ($p < .001$).

Table 8

Results of Hierarchical Linear Models Regressing Student Mathematics Achievement Gains on Teacher MCK as a Continuous and Dichotomous Variable, Condition, and the Teacher MCK-by-Condition Interaction

	MCK as continuous predictor		MCK as dichotomous predictor	
	Model 1	Model 2	Model 1	Model 2
Fixed effects				
Intercept	15.34***	15.41***	15.81***	15.82***
	(0.51)	(0.52)	(0.60)	(0.56)
Teacher MCK	-0.06**	-0.05**	-1.72	-1.79**
	(0.03)	(0.02)	(1.04)	(0.80)
Condition	1.64**	1.54**	1.52*	1.52**
	(0.71)	(0.71)	(0.83)	(0.72)
Teacher MCK * Condition	0.01	–	-0.05	–
	(0.04)		(1.51)	
Variances				
Between Classrooms	8.57***	8.63***	8.79***	8.72***
	(2.93)	(2.94)	(2.96)	(2.95)
Between Students	39.92	39.89	9.66	39.93
	(6.32)	(6.32)	(6.30)	(6.32)

Note. *$p < .10$, **$p < .05$, ***$p < .01$. Model 1 presents results from the moderation analyses. In both analyses, the interaction term was not significant and was excluded from the model to examine the main effects of Teacher MCK and Condition (see Model 2). Standard Errors are reported in parentheses. When examining Teacher MCK as a dichotomous predictor, the variable was coded as 0 = lower three quartiles, 1 = upper quartile.

CHAPTER IV: DISCUSSION

The purpose of the current study was to investigate the interaction between teacher MCK and curriculum (ELM vs BAU) on teacher instructional behaviors (RQ1) and student mathematics achievement (RQ2). With heightened focus from policymakers and professional development leaders on increasing teachers' MCK, along with research indicating that teacher MCK is associated with teaching behaviors and student outcomes, the results of this study contribute to the extant literature by examining MCK in the context of a research-based curriculum (Clarke et al., 2015) compared to BAU curricula. This approach provides a more nuanced look into the effect of teacher MCK on teacher and student outcomes, including how these relationships may vary depending on the curriculum used.

RQ1: Instructional Behaviors

While our research hypotheses did not specify different patterns of findings for the three instructional behaviors examined (i.e., teacher demonstrations, group response opportunities, and individual response opportunities), this emerged in the analyses. Significant interactions also differed depending on the way teacher MCK was examined, either as a continuous or dichotomous predictor of instructional behaviors. Results are summarized separately for each instructional behavior with teacher MCK as a continuous and dichotomous predictor, followed by interpretation of results.

Teacher Demonstrations

When examining teacher MCK continuously, no significant interaction emerged between teacher MCK and condition on teacher demonstrations, though the interaction term was trending toward significance with a *p*-value of .136. Dropping the interaction term from the model, a significant main effect was observed between teacher MCK and the rate of teacher demonstrations, with more knowledgeable teachers providing higher rates of teacher demonstrations regardless of condition. When examining teacher MCK dichotomously, there was a significant interaction between the lower three quartiles and upper quartile of teacher MCK and condition on teacher demonstration rate. Decomposing this interaction revealed that for ELM teachers, the rate of teacher demonstrations was not significantly different depending on level of teacher MCK (rates were 0.592 and 0.556 for the lower three and upper quartiles, respectively). In a 60-minute mathematics lesson, this would translate to ELM teachers providing about 34 teacher demonstrations, regardless of teacher MCK level. For control teachers, there was a higher rate of teacher demonstrations for teachers scoring in the upper quartile of MCK compared to those scoring in the lower three quartiles. Specifically, teachers in the lower three quartiles of MCK had a demonstration rate of 0.462 (about 28 demonstrations in a 60-minute lesson) compared to 0.676 (about 41 demonstrations in a 60-minute lesson) for teachers in the upper quartile of MCK.

The nature of this interaction aligned with our original hypothesis that a positive relationship between teacher MCK and instructional behaviors would emerge for control teachers, but that the instructional behaviors of ELM teachers would be relatively consistent across different levels of teacher MCK. Given that ELM is fully scripted and provides highly specified teacher models, it is not surprising that the rate of teacher demonstrations was consistent across levels of teacher MCK for ELM teachers. Control teachers used curricula that varied in the degree of built-in teacher supports to facilitate demonstrations, such as specific language to model mathematics concepts. Several teachers in the control condition indicated using teacher-developed curriculum materials, which likely did not specify demonstrations of mathematical concepts. It follows that teacher MCK would play a greater role in determining the rate of teacher demonstrations for teachers of BAU curricula.

Group Response Opportunities

Examining teacher MCK both continuously and dichotomously, no significant interactions emerged between teacher MCK and condition on the rate of teacher-elicited group responses. Main effects models revealed that across both analytic approaches, there was a positive relationship between teacher MCK and the rate of teacher-elicited group responses. Additionally, ELM teachers provided a higher rate of group response opportunities overall. Examining teacher MCK continuously, ELM teachers with average MCK had a group response rate of 1.317, eliciting about 79 group responses in a 60-minute mathematics lesson. Control teachers with average MCK had a group response rate of 0.759, eliciting about 46 group responses in the same time frame. Across ELM and control conditions, a 10% increase in teacher MCK resulted in a 0.10 increase in group response rate, or 6 additional group response opportunities in a 60-minute lesson.

While we hypothesized that there would be a significant interaction between teacher MCK and condition on group responses, with ELM teachers eliciting a similar rate of group response opportunities regardless of teacher MCK, this was not the case. The results of the current study suggest that regardless of curriculum, the rate of teacher-elicited group response opportunities was positively associated with teacher MCK. Additionally, across the continuum of MCK, ELM teachers provided higher rates of group response opportunities.

These findings are noteworthy for several reasons. First, although ELM is a fully scripted curriculum, teachers' use of group responses varied depending on their knowledge for teaching mathematics. This suggests that even with highly specified group response opportunities, teachers with varying levels of MCK made use of the curriculum in different ways. Another point of interest is the finding that ELM teachers provided higher rates of group response opportunities across levels of MCK. To further contextualize this, a control teacher with average MCK would need to increase their MKT score by about 50% to equal a teacher with average MCK in the ELM condition. Perhaps the specificity of group response opportunities written into ELM supported teachers with lower MCK to include a higher base rate of group response opportunities compared to teachers in the control condition. It is also possible that ELM teachers with higher MCK went above and beyond, making use of the group response opportunities built into the curriculum but also incorporating more opportunities for students to participate as needed throughout instruction. The fact that curriculum played a role in the rate of teacher-facilitated group response opportunities is in line with previous research that curriculum can influence teacher behaviors and student learning opportunities (Remillard & Reinke, 2012; Remillard et al., 2014).

Individual Response Opportunities

A significant interaction was detected between teacher MCK and condition on individual response opportunities when examining teacher MCK continuously. The pattern of findings indicated that for ELM teachers, as teacher MCK increased, the rate of individual response opportunities increased in a linear manner, whereas for control teachers, there was no relationship between teacher MCK and the rate of individual response opportunities. Specifically, a 10% increase in teacher MCK for ELM teachers resulted in an additional .05 individual response opportunities per minute. This would translate to three additional individual response opportunities in a 60-minute lesson. When examining teacher MCK dichotomously, a significant interaction was not detected (p = .208) and thus main effects models were examined. Across conditions, teachers in the upper quartile of MCK provided higher rates of individual response opportunities, and overall ELM teachers provided higher rates of individual response opportunities after controlling for level of teacher MCK.

The nature of the significant interaction when examining teacher MCK continuously was opposite of our hypothesis that there would be a positive relationship between teacher MCK and instructional behaviors for control teachers, and no relationship for teachers of ELM. On the contrary, a positive relationship between teacher MCK and individual response opportunities was observed for ELM teachers, with no relationship evident for control teachers. This finding could be explained when considering the way that individual response opportunities are presented in the ELM curriculum. Typically, the teacher directions for eliciting individual responses are less specific and include directions such as, “As time allows, call on several children to choose a card and perform an action”, or “Have individual children show you groups of 2 from the chant”. Given that the exact number of individual responses to provide was left open to teacher interpretation, it is possible that teachers with higher MCK differentiated instruction to a greater degree by incorporating more individual practice opportunities for students. Additionally, because the number of individual responses provided were generally based on available instructional time, perhaps teachers with higher MCK made better use of instructional time overall, allowing for more individual response opportunities. In the control condition, teachers provided a similar rate of individual response opportunities regardless of MCK. Examining the instructional behavior data descriptively, on average control teachers provided lower rates of group and individual response opportunities overall (0.77 and 0.46, respectively) compared to ELM teachers (1.34 and 0.65, respectively). Though purely speculation, it is possible that control teachers with higher MCK prioritized different instructional behaviors during their instructional time, such as maximizing group response opportunities. Another possible explanation is that control teachers with lower MCK were more likely to provide individual response opportunities than group ones, and teachers with higher MCK minimized their use of individual response opportunities, resulting in relatively equal rates of individual response opportunities across levels of MCK.

RQ2: Student Mathematics Achievement

We hypothesized that there would be a significant interaction between teacher MCK and curriculum on student mathematics achievement gains, such that for ELM teachers the association would be weaker between teacher MCK and student mathematics achievement compared to teachers of BAU curricula. Contrary to these hypotheses, the results of the current study suggest that there was not a significant interaction between teacher MCK and curriculum on student mathematics achievement. Main effects models were examined and a similar pattern was found when examining teacher MCK continuously and dichotomously; therefore, only the continuous results are discussed here. There was a negative effect of teacher MCK on student mathematics achievement after controlling for condition, such that a one percentage point increase in teacher MCK resulted in a decrease in student mathematics achievement gain scores by 0.05 points. By these same parameters, a 10% increase in teacher MCK would result in a 0.50-point decrease in student mathematics achievement gain scores. There was a positive effect of ELM on student mathematics achievement, resulting in an increase in student mathematics achievement gains by 1.54 points after controlling for MCK.

The finding that teacher MCK had a negative effect on student mathematics achievement gains is surprising given other research indicating a positive relationship between the two variables (e.g., Hill et al., 2004; Hill et al., 2005). Given that the results of this study are limited to our specific sample across just two states, we use caution when interpreting this finding. Additionally, while a negative effect was observed, the clinical significance of a 0.50 decrease in student mathematics achievement gains following a 10% increase in teacher MCK is debatable.

Nevertheless, the negative effect of teacher MCK is interesting and warrants discussion. One consideration with the current sample of students is that a large number of students were identified as at-risk (defined as ≤ 40th percentile on the TEMA-3, including 66% of the sample in Clarke et al., 2011, and 50% of students in Clarke et al., 2015). Teacher MCK has largely been investigated across students with a broader range of mathematical skill, and so it is possible that it may have differential associations with mathematics achievement for a sample of students with a higher degree of risk. A second consideration is the role that higher mathematics education may play in impacting both teacher MCK and pedagogical practices. In the current sample, teacher MCK was positively correlated with the number of mathematics courses taken ($r = .24$, $p < .01$). Pre-service and in-service general education teachers are increasingly being encouraged to adopt constructivist practices (Liang & Akiba, 2015; Richardson, 2003), which is the "dominant pedagogical theory in contemporary educational circles" (p. 98, Krahenbuhl, 2016). Constructivist practices are often "student-centered" in nature, with students making meaning and discovering answers to problems with less teacher guidance (Krahenbuhl, 2016). While this approach may be beneficial for students with a strong foundation in mathematics, students at-risk for mathematics difficulties may struggle with the absence of clear teacher modeling and feedback. Though this is purely speculative, it is possible that teachers with higher MCK were also more likely to engage in constructivist teaching practices, which could have a negative impact on student mathematics achievement gains for a more at-risk sample. Kutaka et al. (2017) implemented an 18-credit graduate mathematics education program, *Primarily Math*, and found that participating teachers increased their MCK within Number and Operations and also their beliefs supporting constructivist practices relative to teachers in a comparison condition. There may accordingly be some association of increased teacher MCK with constructivist views. Future research should investigate associations between teacher MCK and student mathematics achievement across varying levels of student skill to determine whether associations differ for students that are at-risk versus compared to those that are on track in mathematics. Additionally, researchers should consider posing more nuanced questions such as examining associations of pedagogical approaches with teacher MCK, implementation of mathematics curricula, and student learning outcomes.

Another notable finding from examining the nested models is that while controlling for teacher MCK, the effect of ELM resulted in a 1.54-point increase in student mathematics achievement gains. This demonstrates that evidence-based curricula, with built-in teacher supports and based in principles of effective mathematics instruction, can have a positive impact on student mathematics achievement.

Limitations & Future Research Directions

The findings of the current study must be considered in light of several limitations. First, given that the documented effect of teacher MCK is small (e.g., Agodini & Harris, 2016) and that there were only ~64 teachers per condition, there was limited power to detect interaction effects in our analyses. This was countered by expanding the definition of statistical significance to $\leq .10$, though it should be noted that the majority of significant findings fell within the more traditional range of $< .05$. Second, previous research using the ELM dataset indicates that the reliability of the COSTI-M in the current dataset was variable, with stability ICCs ranging from .26 to .44 (Doabler et al., 2018). It is possible that stronger relationships between teacher instructional behaviors and other variables would be observed with more accurate measurement of instructional behaviors including an increased number of observations. Additionally, while the COSTI-M provides an indicator of the rate of instructional behaviors, it does not include a measure of instructional quality. It is possible that variables outside of the scope of the COSTI-M, such as the quality of teacher models or group response opportunities, would shed light on relationships with other variables above and beyond the rate of instructional behaviors.

Third, while the specific curricula that control teachers used was documented on a survey item, it would be useful to have more information about instruction in the control condition, including what curricula was used (if any) by the seven teachers that did not respond to the item. Additionally, because teachers in the control condition used a variety of different curricula, it is hard to pinpoint specific curricular features that may have resulted in interaction effects on teacher instructional behaviors. An examination of the most commonly-used BAU curricula revealed that around 70% of control teachers were using programs that have been described in the research as having minimal or low teacher support. Nonetheless, one can only draw conclusions about features of ELM compared to a range of BAU curricula in the control condition that may or may not have included similar features. Last, given that ELM was implemented in the context of a larger RCT, ELM teachers received additional support including three four-hour PD sessions throughout the academic year. Whether control teachers received similar levels of support from curriculum developers or internal coaches is unknown. While we consider it unlikely given the research demonstrating that PD alone typically does not impact teacher behavior (e.g., Garet et al., 2011), it is possible that the PD influenced teacher behaviors or interacted in such a way that teachers were more likely to make better use of the ELM curriculum compared to teachers of control curricula.

Final Thoughts & Conclusions

Given the national focus on increasing student mathematics achievement through teacher variables such as increasing teachers' MCK, the current investigation presents a timely exploration of possible mechanisms to move the dial on student mathematics achievement. Several findings are particularly worthy of revisiting. The results of the current study indicate that teacher MCK did influence teachers' implementation of the ELM curriculum across two of the three instructional behaviors examined. ELM teachers with higher MCK provided higher rates of both group and individual response opportunities compared to teachers with lower MCK. This supports prior research indicating that different teachers make use of curricula in different ways (Remillard et al., 2014) and that teacher MCK plays a role in curriculum effects (Agodini & Harris, 2016).

These findings have implications for curriculum developers, professional development leaders, and districts selecting core mathematics curricula, in regards to how teachers with varying backgrounds might make use of different curricular programs and features. The results of the current study indicate that both teacher MCK and curricular features may contribute to teachers engaging in different instructional behaviors. Additionally, while districts should consider that the training and mathematical background of their teachers may impact implementation of curricula, the results of the current study also suggest that curricula with a high degree of implementation support have the power to shape the instructional behaviors of teachers above and beyond MCK.

Of equal interest is the need for further exploration of the role that teacher MCK and other teaching variables have on student mathematics achievement, particularly for at-risk students. The results of the current study suggest that overall, teacher MCK had a small but negative effect on student mathematics achievement gains, whereas ELM had a positive effect. Given that the effect of teacher MCK was somewhat negligible from a clinical standpoint, targeting curricula with a high degree of implementation support that can be used by teachers with a range of skillsets may be a more practical and effective way to increase student mathematics achievement. While this study begins to unpack for whom and in what contexts curricula can be effectively implemented, future investigations of teacher and student characteristics are warranted. Developments in this line of research may help increase our knowledge base of how to best support teachers across the continuum of mathematical knowledge to effectively implement curricula, and ultimately lead to increased student outcomes across the board.

APPENDIX A

ELM ALIGNMENT WITH CCSS-M

(2010; SEITZ DAVIS & JUNGJOHANN, 2014)

Alignment of ELM Objectives to the Common Core State Standards

The following pages show the alignment of ELM Objective and the Common Core State Standards across the four quarters.

	Counting and Cardinality	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
	Know number names and the count sequence.				
1	Count to 100 by ones and by tens.	to 10	to 30 by 10s	to 60	to 100
2	Count forward beginning from a given number within the known sequence (instead of having to begin at 1).	<10	<20		<30
3	Write numbers from 0 to 20. Represent number of objects with a written numeral 0-20.	0-10	0-20		
	Count to tell the number of objects.				
4	Understand the relationship between numbers and quantities; connect counting to cardinality.	√	√	√	√
	a. When counting objects, say the number names in the order, pairing each object with one and only one number name and each number name with one and only one object.	0-10	0-20		
	b. Understand that the last number name said tells the number of objects counted. The number of objects is the same regardless of their arrangement or the order in which they were counted.	0-10	0-20		
	c. Understand that each successive number name refers to a quantity that is one larger.	0-10	0-20		
5	Count to answer "how many?" questions about as many as 20 things arranged in a line, a rectangular array, or a circle, or as many as 10 things in a scattered configuration; given a number from 1–20, count out that many objects.	0-10	0-20		

	Compare numbers.	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
6	Identify whether the number of objects in one group is greater than, less than, or equal to the number of objects in another group, e.g., by using matching and counting strategies. (Include groups with up to ten objects)	√			
7	Compare two numbers between 1 and 10 presented as written numerals.		√		
	Operations and Algebraic Thinking	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
	Understand addition as putting together and adding to, and understand subtraction as taking apart and taking from.				
1	Represent addition and subtraction with objects, fingers, mental images, drawings, sounds, acting out situations, verbal explanations, expressions, or equations.		Add	subt	√
2	Solve addition and subtraction word problems, and add and subtract within 10, e.g., by using objects or drawings to represent the problem.		Add	subt	√
3	Decompose numbers less than or equal to 10 into pairs in more than one way, e.g., by using objects or drawings, and record each decomposition by a drawing or equation.		√	√	√
4	For any number from 1 to 9, find the number that makes 10 when added to the given number, (using objects or drawings, and record the answer with a drawing or equation).			√	√
5	Fluently add and subtract within 5.		w/obj	√	√
	Number and Operations in Base Ten	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
	Work with numbers 11–19 to gain foundations for place value.				
1	Compose and decompose numbers from 11 to 19 into ten ones and some further ones, e.g., by using objects or drawings, and record each composition or decomposition by a drawing or equation (e.g., 18 = 10 + 8); understand that these numbers are composed of ten ones and one, two, three, four, five, six, seven, eight, or nine ones.		√		

	Measurement and Data	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
	Describe and compare measurable attributes.				
1	Describe measurable attributes of objects, such as length or weight. Describe several measurable attributes of a single object.	√			√
2	Directly compare two objects with a measurable attribute in common, to see which object has "more of"/"less of" the attribute, and describe the difference. For example, directly compare the heights of two children and describe one child as taller/shorter.	√	√	√	√
	Classify objects and count the number of objects in each category.	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
3	Classify objects into given categories; count the numbers of objects in each category and sort the categories by count. (Limit category counts to be less than or equal to 10.)	√	√	√	√
	Geometry	**1st Q**	**2nd Q**	**3rd Q**	**4th Q**
	Identify and describe shapes (squares, circles, triangles, rectangles, hexagons, cubes, cones, cylinders, and spheres).				
1	Describe objects in the environment using names of shapes, and describe the relative positions of these objects using terms such as above, below, beside, in front of, behind, and next to.	√	√	√	√
2	Correctly name shapes regardless of their orientations or overall size.	√	√	√	√
3	Identify shapes as two-dimensional ("flat") or three dimensional ("solid").				√
	Analyze, compare, create, and compose shapes.				
4	Analyze and compare two- and three-dimensional shapes, in different sizes and orientations, using informal language to describe their similarities, differences, parts (e.g., number of sides and vertices/"corners") and other attributes (e.g., having sides of equal length).	√	√	√	√
5	Model shapes in the world by building shapes from components (e.g., sticks and clay balls) and drawing shapes.		√	√	√
6	Compose simple shapes to form larger shapes. For example, "Can you join these two triangles with full sides touching to make a rectangle?"				√

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