Pre-Kindergarten mathematics & science: Design-based research on curricular development.

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5 authors, including:

Mable Kinzie
University of Virginia

Jessica E Vick Whittaker
University of Virginia

Patrick Mcguire
University of Colorado Colorado Springs

Youngju Lee
Korea National University of Education

Research on Curricular Development for Pre-Kindergarten Mathematics and Science

MABLE B. KINZIE

University of Virginia

JESSICA VICK WHITTAKER

University of Virginia

PAT MCGUIRE

University of Colorado at Colorado Springs

YOUNGJU LEE

University of Virginia

CAROLYN KILDAY

University of Virginia

Background/Context: *As increasing attention is paid to preparing students to succeed in school, the development and adoption of research-based curricula have become progressively more important. However, many curricular designs lack a basis in scientific evidence; research and curricular design are frequently treated as two separate enterprises.*

Purpose/Objective: *In this paper, we present the Research on Curriculum Design (RCD) model, first advanced by Clements in 2007, with results from its application to the design and iterative development of pre-kindergarten mathematics and science curricula.*

Research Design: *RCD is an example of design-based research, with the additional specific goals of the production of an effective curriculum and the evolution of theoretical guidelines to inform future curricular designs. Our implementation spanned two years and involved iterative development and testing of two, year-long curricula.*

Findings/Results: *Application of RCD methods informed our understandings of the target population, the knowledge and skills to be developed, and the theoretical and research-based models that guided the designs. Subsequent iterative development and evaluation in five pre-K classrooms enabled refinement of the curricular design, as well as the evolution of design*

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guidelines useful for informing future curriculum development efforts. A culminating test of the resulting curricula in eight pre-K classrooms suggests the success of the RCD approach, yielding high-quality, high-fidelity teacher implementation, with teacher fidelity and curricular dosage predicting students' mathematics learning gains across the year.

Conclusions/Recommendations: *Results support the value of the RCD model for achieving research-based curricula that have the potential to effectively support teachers in their practice and positively impact children's early learning.*

A major drawback of many curricula is the absence of scientific research guiding their development—the curricula are not informed by research on teaching and learning, and are not rigorously tested with teachers and students (see, Clements, 2004, for discussion of these drawbacks in early childhood mathematics; Kesidou & Roseman, 2002, draw similar conclusions regarding middle school science curricula). These shortcomings are not surprising, as the foci of research and of curriculum development are often thought to be different: Research is aimed at the creation of knowledge, while curriculum development focuses on the production of learning materials (Clements, 2007). The two can be brought together in meaningful ways (Clements, 2007), improving the quality of the curriculum and also informing the fields of curricular and instructional design. Drawing upon research methods to create the best possible curricula is increasingly important in a time when meeting learning standards is receiving substantial national attention (see, for example, movement toward widespread adoption of the Common Core standards, now endorsed in 45 states; Common Core State Standards Initiative, 2012), but the curricular materials some teachers receive is not much more than a set of learning standards (Kauffman, Johnson, Kardos, Liu, & Peske, 2002).

Research on Curricular Development (RCD) offers a rich methodology to help bridge these gaps, and this paper is intended to provide an example of the RCD process applied to the design, development, and evaluation of pre-kindergarten mathematics and science curricula. We selected these domains for curricular development due to the foundational critical thinking skills that are supported by these domains (e.g., Klahr, Zimmerman, & Jirout, 2011), the ability to integrate multiple content areas (e.g., language, literacy, etc.) into mathematics and science activities, and the importance of early mathematics and science knowledge and skills in supporting children's later academic development (Claessens & Engel, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; National Mathematics Advisory Panel [NMAP], 2008).

Designed for use in pre-kindergarten, *MyTeachingPartner-Mathematics/Science (MTP-M/S)* is intended to encourage students' curiosity, engagement, and learning, and to support teachers' curricular implementation, especially for teachers with little experience in mathematics and science education. In this paper, we describe how we used the RCD process to design, develop, and test the efficacy of these curricula. We share what was achieved with application of the RCD model and close with observations on the value of this approach for research on and development of educational products.

RESEARCH ON CURRICULAR DEVELOPMENT AND RCD RESEARCH QUESTIONS

Curricular development can involve several different foci: the specification of a body of knowledge to be shared, identifying the learning outcomes that students need in order to succeed in school and life, or the articulation of instructional interactions that support students' motivation, engagement, and learning (Smith, 1996, 2000). We pursued the curricular development of *MTP-M/S* in order to focus on all of these. Our research questions for this RCD undertaking are informed by Clements' 10-step approach to curriculum research (2007), reframed to reflect four predominant foci:

1. What are the knowledge and skills to be developed by pre-kindergarten mathematics and science curricula?
2. Which theoretical and research-based models of student learning and teacher practice should inform our activity designs?
3. What was learned through iterative development and evaluation, to inform the foundations for curricular design?
4. Do teachers implement the curricula with high fidelity and report that it is useful to their practice? Is fidelity of implementation related to child outcomes?

Our review of the literature, theory, and current practices will be presented in response to the first two questions. Our development process will be described to answer question three. During this process, we iteratively designed, developed, and evaluated the curricula, together with pre-kindergarten teacher–partners from five classrooms during year one. During the second year, we conducted a test of the curricula with the teachers and students in eight other pre-K classrooms; teachers' reports of their satisfaction with the results of classroom observations of engagement will be presented in response to question four, as described in Table 1.

Table 1. Research Question, Project Year Addressed, & Tasks Performed/Data Collected

Research Question	Project Year	Tasks Performed/Data Collected
RQ 1: What are the knowledge and skills to be developed by a pre-kindergarten mathematics and science curriculum?	One	Literature Review
RQ 2: Which theoretical and research-based models of student learning and teaching beliefs/practice should inform our activity designs?	One	Literature Review
RQ 3: What was learned through iterative development and evaluation, to inform the foundations for curricular design?	One	Design/Development/Evaluation in five pre-kindergarten classrooms
RQ 4: Are the resulting curricula effective?	Two	Implementation Test of the curricula, in eight pre-kindergarten classrooms.

RESEARCH QUESTION #1: WHAT ARE THE KNOWLEDGE AND SKILLS TO BE DEVELOPED BY PRE-KINDERGARTEN MATHEMATICS AND SCIENCE CURRICULA?

Research Question 1 was addressed with a thorough review of the literature (as was Research Question 2, which follows). Psychology and education databases were searched for relevant studies. Manuscripts from the past 10 years in early childhood education, developmental psychology, and mathematics and science education journals were examined. Reports from the National Research Council (NRC), National Center for Educational Statistics (NCES), National Association for the Education of Young Children (NAEYC), and National Council of Teachers of Mathematics (NCTM) were reviewed. The resulting information was synthesized and is summarized below.

RQ 1.A. WHAT ARE THE CHARACTERISTICS AND LEARNING NEEDS OF THE TARGET POPULATIONS?

Pre-Kindergarten Education

Children growing up in poverty or social disadvantage often enter school without the knowledge and skills critical to school success (NCES, 2009; NMAP, 2008)—the result of an “opportunity gap” in their learning experiences (Gutierrez, 2008). Pre-kindergarten (pre-K) programs were established to help meet the needs of these children, including fostering their knowledge and skills in the areas of mathematics, science, language, and early literacy (Bowman, Donovan, & Burns, 2001). While limited longitudinal research has been conducted on the effects of early mathematics and science curricular implementations, comprehensive multidisciplinary early childhood programs have been examined over the longer term, with related estimates of return on investment ranging from 4–1 to 16–1 over an individual's lifespan, through savings on school remediation and health, welfare and justice programs, as well as more stable marriages and higher income (National Association of State Boards of Education, 2006; Schweinhart et al., 2005).

To realize this potential, significant attention must be paid to the design and implementation of these early learning experiences, which have been found to vary substantially in both *quality* of instruction and the *content* addressed (Bowman et al., 2001). High quality experiences are particularly important for students at risk of early school failure; it is these students who are more likely to receive lower-quality educational experiences (LoCasale-Crouch et al., 2007). A recent analysis integrating a review of 84 preschool programs found that the most important aspects of quality in early education are high-quality teacher–child interactions and the use of effective curricula (Duncan & Magnuson, 2013). There is some evidence that domain-focused curricula, rather than global curricula, produce greater gains in children's academic outcomes (Preschool Curriculum Evaluation Research Consortium, 2008).

Early Childhood Mathematics and Science

Young children are capable of developing substantial informal mathematical and scientific knowledge through play and as a function of engaging with the world (Clements, 2004; Duschl, Schweingruber, & Shouse, 2007). These understandings are particularly important, as they serve as the foundation for mathematical and scientific literacies required for full engagement with the phenomena, creative problem solving and collaboration, and learning opportunities presented in everyday life (NAEYC and NCTM, 2002; NRC, 2006).

Mathematics and science are two domains that support the development of children's critical thinking skills, and early knowledge and skills in math and science are foundational for subsequent learning across domains (Grissmer et al., 2010; NMAP, 2008; Sarama, Lange, Clements, & Wolfe, 2012; Weiland, Eidelman, & Yoshikawa, 2011).

Definitions of critical thinking skills vary, although they almost all include the ability to analyze arguments, make inferences, use reasoning, and make decisions to solve problems (Lai, 2011). Some researchers have concluded these skills are domain specific (e.g., reasoning skills in science would not transfer to mathematics); however, others have argued that there is a set of general critical thinking skills that can be fostered in young children (see Lai, 2011, for a review). The domain of science in particular lends itself to teaching children how to formulate hypotheses, design experiments, and evaluate evidence (Klahr et al., 2011). For example, Klahr and colleagues (2011) note science education aims to help children master the skills of discovering, assessing, revising, and communicating knowledge. These skills are used across all learning domains, and thus are critically important for school success.

In addition to supporting children's critical thinking skills, children's foundational knowledge in math and science is important for their later learning in these domains (Grissmer et al., 2010; NMAP, 2008), and is increasingly being found to predict development in other domains (Sarama et al., 2012; Weiland et al., 2011). Current research suggests that children's early math skills are the strongest predictor of later academic success (Hooper, Roberts, Sideris, Burchinal, & Zeisel, 2010; Pagani, Fitzpatrick, Archambault, & Janosz, 2010). In fact, children's mathematical knowledge at school entry is a more significant predictor of later academic success than are early reading skills (Duncan et al., 2007). Children's early science skills have also been shown to be important predictors of later academic functioning. In a recent analysis of six longitudinal data sets, researchers found that the strongest early predictor of children's later science and reading skills, and a strong predictor of later math skills, was their thinking and reasoning skills, including their ability to formulate questions about the natural world, gather evidence, and communicate answers (Grissmer et al., 2010).

Unfortunately, large national studies show that by age 4, fewer children born into poverty demonstrate key mathematical skills (number sense and geometry) compared to their more advantaged counterparts (45% compared with 72%) (NCES, 2009), a pattern accentuated as children start school and move into the primary grades (NCES, 2004). Limited attention is paid to mathematics (NAEYC & NCTM, 2002), for which the focus generally has been limited to counting and shape identification (Balfanz, 1999). A similar pattern is seen in science, where the focus is often on displays of science materials or art projects involving them, with teachers rarely encouraging related inquiry (cf. NRC, 2005). Findings from the Multi-State Study of Pre-Kindergarten and the Study of State-Wide Early Education Programs (SWEEP; Early et al., 2010) indicate that across the classroom day, little instructional time was spent on mathematics (8% of the time) and science (11%), compared to language and literacy (17%) and "no coded learning activity" (44%). (Similar findings have been obtained in other studies; see also Graham, Nash, & Paul, 1997; Stipek, 2008; and Tu, 2006.) The need for additional, high-quality early mathematics and science learning opportunities is clear; next we will present our findings relative to the knowledge and skills that should be developed.

RQ 1.B. WHICH CONCEPTS AND SKILLS ARE THOUGHT TO BE MOST IMPORTANT, AND HOW CAN WE ENSURE CURRICULAR FIT AND ADOPTION?

In their review of the research on early childhood education, Bowman and colleagues (Bowman et al., 2001) concluded that "developing expertise requires both a foundation of factual knowledge and skills and a conceptual understanding that allows facts to become 'usable'" (p. 185). Exactly what this knowledge and these skills should be has been the focus of national educational organizations in mathematics and science.

Important Mathematics Concepts and Skills: Identification and Ensuring Fit

The NCTM, the primary professional organization representing the discipline of mathematics education, released the *Curriculum Focal Points for Prekindergarten through Grade 8 Mathematics* (2006) based on an exhaustive review of curricula from multiple states and other countries as well as existing research. The study identifies three "significant mathematical targets" at each grade, unifying and building professional consensus from what had been inconsistently articulated state standards across the United States. At the pre-kindergarten level, the focal points target number and operations, geometry, and measurement.

The developmental trajectories (progressions in students' thinking and/or learning activities) articulated by Clements (2004), the "big ideas" of early mathematics explicated by Ginsburg (Ginsburg & Ertle, 2008; Greenes, Ginsburg, & Balfanz, 2004), and reviews of the research by leaders in early childhood mathematics (Clements & Sarama, 2004) were influential in our articulation of goals and objectives for *MTP-M/S*. We also conducted our own reviews of research on children's development of skills in oral and object counting, whole number operations, geometry, and measurement.

Our review also included the state standards for pre-kindergarten mathematics and existing mathematics curricula, to validate the importance and fit of our identified mathematics concepts and skills. We identified 13 pre-kindergarten mathematics standards endorsed across 35 states (each standard was endorsed by an average of 20 states [range = 7 to 34 states for a single standard; *SD* = 10.33]). All but one standard directly corresponded to one of the three NCTM focal points. (In nine states, determining the probability of events had been identified as a pre-kindergarten mathematics standard but did not directly correspond to one of the NCTM focal points. This skill is, however, relevant to scientific inquiry skills and we included it in the science curriculum.) Therefore, we felt confident that designing a curriculum to address the NCTM focal points was a valid starting point, as we found them to be in alignment with what is known about early mathematics learning and with what states have identified as important for their students to learn. A review of existing curricula in early childhood mathematics, including *Building Blocks* (Clements & Sarama, 2007), *Big Math for Little Kids* (Ginsburg, Greenes, & Balfanz, 2003), *Numbers Plus* (Epstein, 2006), and *Pre-K Mathematics* (Klein, Starkey, & Ramirez, 2002), supported this approach; similar mathematical concepts and skills are addressed in these curricula, which explicitly target the NCTM focal points. The domains of *MTP-Math* were defined to include:

- Number (Oral Counting, Object Counting, and Numeral Recognition, including concepts foundational to Place Value),
- Operations (Equal Partitioning and Combining/Separating),
- Geometry (Shapes and Patterns), and
- Measurement (Length, Weight, and Area/Volume).

Important Science Concepts and Skills: Identification and Ensuring Fit

The National Science Education Standards were developed with input from many stakeholder groups in order to bring consistency to the knowledge and skills needed to develop scientific literacy (NRC, 2006). The standards for grades K-4 address physical life, earth and space, science and technology, science in personal and social perspectives, and the history and nature of science. Implicit in these standards is students' pursuit of inquiry as an active way of developing an understanding of the facts, concepts, principles, etc., that comprise scientific knowledge, with explicit guidance from teachers. We also consulted the Benchmarks for Science Literacy, produced by the American Association for the Advancement of Science (AAAS, 1993), referencing the benchmarks for grades K–2. Next, we conducted a literature review to identify what young children understand (and misunderstand) about the physical science concepts of objects and properties, motion and force, light and sound; the earth science concepts of weather, night and day, and moon phases; and the life science concepts of living and nonliving. The literature describing the development of young children's scientific thinking was also synthesized.

We also reviewed state standards for pre-kindergarten science education from the 12 states where these had been articulated (not all states advancing pre-kindergarten standards included science standards). We found 33 different standards identifying important science concepts and/or scientific inquiry skills. The greatest degree of convergence was evident in the 11 standards describing scientific inquiry skills; these standards were endorsed by just over half of the states. About half of the states also showed agreement on six life science standards and six physical science standards. Within the domain of earth science, there was the least convergence across the states for the 10 related standards, with each of these adopted by about one-fourth of the states. In comparing these state standards to the national standards advanced by the NRC and AAAS, we found that the national standards covered almost all of the state standards.

We reviewed four prominent science curricula for pre-kindergarten, *ScienceStart!* (French, 2004), *PreSchool Pathways to Science* (*PrePS*; Gelman & Brenneman, 2004), the *Young Scientist Series* (Chalufour & Worth, 2003, 2004, 2005), and *Early Childhood Hands-On Science (ECHOS)* (Brown & Greenfield, 2010; Greenfield et al., 2009). Each clearly addresses learning objectives in alignment with the national standards. Although there are differences between curricula in their coverage of specific science concepts, all emphasize science inquiry skills such as prediction, observation, and recording and analysis of observations, as well as relevant vocabulary.

The resulting domains explored across *MTP-Science* include:

- Life Science (Humans, Animals, and Plants),
- Earth Science (Weather, Day/Night, and Earth Materials), and
- Physical Science (Properties of Materials, Movement, and Physical Change).

Through early teacher focus groups in three school districts, we came to understand that the development of students' mathematics and science concept knowledge and skills was uneven across classrooms. Although most teachers did report emphasizing number sense (counting and numeral recognition) and geometic shapes, few reported any activities related to operations or measurement. In the science domain, teachers were quite fond of the science activities they employed (e.g., science centers with seasonally gathered materials, the baking soda and vinegar "volcano," etc.); however, teachers were unable to articulate the understandings they hoped students would develop from these activities. Other researchers have documented similar findings (NRC, 2005). Based on teachers' responses during our focus groups, it also appeared their emphasis on mathematics and science activities was more on children *doing* and less on children *reflecting on* what they had done and observed. These themes proved to be important in the evolution of our curricular design, as we will later describe.

RESEARCH QUESTION #2: WHICH THEORETICAL AND RESEARCH-BASED MODELS OF STUDENT LEARNING AND WHICH TEACHING BELIEFS/PRACTICE SHOULD INFORM OUR ACTIVITY DESIGNS?

The limited time and attention paid to development of mathematical and scientific thinking at the pre-kindergarten level may be a function of teacher beliefs about children's early development. First, a prevailing conviction is that young children are not developmentally ready to learn formal mathematics and science concepts. In their review of child development theory, Gelman and Brenneman (2004) observe that the age-related stages of development advanced by Piaget involve cognitive development but preclude children's ability to engage in abstract thought. These beliefs, however, are not supported by research findings (Bowman et al., 2001; NMAP, 2008), which instead suggest that careful scaffolding of skill development, even at young ages, can lead to children's learning in these domains (Duschl et al., 2007).

Second, many early childhood educators continue to feel that early learning is best accomplished through children's play and self-discovery, with the teacher's primary role being to support that process through recognition of "teachable moments" across the school day. Done well, this approach can be highly effective in supporting children's learning. Some researchers assert, however, that preschool teachers spend little time in the observation necessary to perceive these moments, and even if teachers are able to recognize the undergirding concepts and skills that would be relevant to build upon, it is difficult for them to decide how to respond in the moment (Ertle et al., 2008). This is thought to be in part a function of inadequate teacher training and lack of teacher confidence, as well as the fact that "the difficulty of teaching young children mathematics [we submit the same is true for science] is typically underestimated" (Stipek, 2008, p. 13).

Balancing Between Student-Centered and Teacher-Guided Exploration

In response to the above, we sought to balance meaningful student-centered interactions relevant to children's everyday experience, and teacher-guided, explicit exposures to key mathematics and science skills and concepts, as recommended by Justice and Pullen (2003). This approach is in alignment with research suggesting the value in both "student-centered" and "teacher-directed" approaches (NMAP, 2008; in fact, speaking for NAEYC, Snow, 2011, observes that the tension between play and direct instruction is a false dichotomy and a distraction—that we need a balance of both for high-quality early childhood education). Vygotskian theory supports the value of adult guidance to enrich children's learning (French, 2004; Gelman & Brenneman, 2004) and substantial research exists that points to the importance of explicit teacher guidance, particularly for novice learners (Kirschner, Sweller, & Clark, 2006; Klahr et al., 2011).

Anchored Investigations as Well as Intentional Teaching

Theorists contend that knowledge is situated in authentic experience, with richer understandings developing as a function of more active engagement with the activity, tools, and culture of that context (Brown, Collins, & Duguid, 1989). Based on research, the National Mathematics Advisory Panel (NMAP, 2008) concluded that learning via real-world contexts offered a significant performance advantage when assessments have involved similar authentic problems, but no advantage for performance on other aspects of mathematics knowledge and skills, including operations tasks and simple word problems. Therefore, we determined that it was important to offer activities relevant to authentic life experiences but *also* to focus explicitly on development of specific knowledge and skills, as recommended by Ginsburg and Ertle (2008): "Intentional teaching can satisfy children's intellectual needs at the present time and also liberate their growth" (p. 46).

Supporting High-Quality Teacher–Child Interactions

Research on child development indicates that the interactions between children and adults are a primary motivator of student learning and social development (Hamre & Pianta, 2007; Mashburn & Pianta, 2006; Rutter & Maughan, 2002). Teacher-child interactions can be organized into three categories. *Emotional Support* describes the extent to which teachers are senstive, responsive, and engaged with preschool students; it is positively associated with growth in social competence, reading, and mathematics (Curby, Rimm-Kaufman, & Ponitz, 2009; Pianta, Belsky, Vandergrift, Houts, & Morrison, 2008). A well-managed classroom is characterized by clear expectations for student behavior, productivity, and a variety of modalities for learning; the presence of these kinds of *Classroom Organization* is associated with gains in learning (Soar & Soar, 1979) and behavioral development (Emmer & Stough, 2001). Finally, *Instructional Support* is denoted by the extent to which teachers develop concepts, provide feedback, and model advanced language, and is associated with increased language and cognitive outcomes (Mashburn et al., 2008). We drew from the research on effective teacher–child interactions in all of these areas (Hamre, Pianta, Mashburn, & Downer, 2007) in the design of *MTP-M/S* activities.

RESEARCH QUESTION #3: WHAT WAS LEARNED THROUGH ITERATIVE DEVELOPMENT AND EVALUATION TO INFORM THE FOUNDATIONS FOR CURRICULAR DESIGN?

We responded to this research question through cycles of design/development/evaluation. Here we describe the participants and this process that led to the iterative refinement of the curricula, along with emergent design guidelines that can inform future curriculum development efforts.

Design Team Members

Individuals with multiple skill sets were involved in the iterative development, including:

- mathematics and science education experts (one senior educational expert in each area),
- early childhood educators (two on the design team in addition to two cadres of practicing teachers who informed our work, one during iterative development [see below] and another during the curricular test [see Research Question 4]),
- developmental psychologists (two on the design team), and
- instructional designers (one lead plus four designers).

The team was deployed as follows: The mathematics and science curricula were each created by a development group, with a resident expert in mathematics or science education and two instructional designers to collaborate on building and testing the curricula. The instructional design lead established and monitored the curricular development and testing procedures and served as design consultant to both groups, along with the developmental psychologists and experienced early educators. Two additional personnel were nationally recognized experts, one in early mathematics education and one in early science education, who also reviewed the curricula in entirety and provided recommendations for refinement.

Five pre-K teachers served as participants in an iterative development process, implementing early versions of the curricula in their classrooms, and providing feedback. The teachers were selected from pre-kindergarten classrooms serving children with one or more risk factors for later school failure (poverty, second language learners, or health or developmental problems). All teachers held a bachelor's degree and were certified to teach 4-year-old children.

Curricular Evaluation: Data Sources and Process

Iterative process. An iterative, user-centered, *rapid-prototyping* approach helps designers ensure that products are effective and engaging (see Kinzie, Cohn, Julian, & Knaus, 2002, for an overview). We began by creating early prototypes of instructional activities and sending them out for review and implementation by five teachers in the fall of the first year. Based on teacher feedback and our observations, we made substantial midyear changes (described below) and began again, with three of the teachers implementing another four months of the curricula in the spring of year one. Based on the evaluative data collected, we revised these months of the curricula and went on to develop the remaining five months of the curricula. This version of the material was implemented during the second year's test of the curriculum (see Research Question #4).

Video observations. We collected videotaped observations of all of the activities implemented by participating teachers. To do this, we provided them with a video camera and tripod and asked them to leave the camera set up in their classroom, turning it on five minutes before beginning any of our activities and turning it off after concluding and transitioning to the next activity. At the end of year one, we reviewed all videotapes received from the five participating teachers, in order to inform our curricular revisions. An experienced early childhood educator trained and reliable on a measure of teaching quality, the *Classroom Assessment Scoring System* (CLASS, Pianta, La Paro, & Hamre, 2008; see description under Research Question 4), conducted the videotape review using the CLASS framework to guide her observations. She documented these along with descriptions of specific problems in the activity design or implementation, teacher-supplied modifications deemed to be effective, and the duration of the activity (we targeted 15–20 minutes per activity). To these notes, we later incorporated teachers' written evaluations for every activity, and completed the review by suggesting needed revisions based on these data. The curricular development groups then collectively reviewed the corpus of this information (see below).

Teacher feedback. Teachers wrote evaluative comments after implementation of each activity, participated in focus groups and an end-of-year teacher interview, and completed an end-of-year teacher survey. Across these forms of feedback, teachers shared perceptions of the curricula and offered recommendations for improvement.

Expert review. We sent the mathematics and science curricula out for review by two external experts, who were developmental psychologists as well as being nationally recognized authorities in early childhood mathematics or science education. They provided detailed comments and recommendations for refinement of all activities.

Development group reviews/revisions. This review and revision process took place in several phases and involved synthesis of multiple forms of data. The mathematics and science development groups reviewed the video observation notes and teacher feedback, considered the feedback from the expert reviewers, and reviewed at least one additional videotape for every activity before determining and making needed revisions. The resulting *MTP-M/*S curricula include two mathematics and two science activities every week, along with one related mathematics or science center every week (centers were included for eight of the nine months), for a total of 165 activities/centers across the school year.

Figures 1 and 2 provide illustrations of the 10–25 minute activities making up the two curricula. In these activities, there is teacher guidance, but also opportunities for students to explore and directly experience aspects of the critical concepts for which understanding is being developed. Within the first mathematics activity on volume (see Figure 1), for example, the teacher elicits students' help in discovering how much each of three containers can hold. Students fill each of the containers in turn with scoops of rice, noting the number of scoops each holds. Through their hands-on engagement with this process they develop a kinesthetically informed understanding of the concept of volume. When the teacher asks which will hold the most, students work on ordering the jars from the smallest to the largest in volume. Students continue this exploration with new containers. Finally the teacher poses questions for students to consider, as they discuss what volume is, why it matters, and how considering a container's volume can be helpful to them. These understandings are extended by considering the volume of containers encountered across the classroom day; in a later activity, students are challenged to make predictions about the volume of novel containers.

A similar approach is taken in science activities (see Figure 2). For instance, after exploring and developing an understanding of the concepts of solid and liquid in earlier activities, the teacher introduces an activity by giving students ice cubes to suck on, asking them to think about whether this ice is a solid or a liquid. This change in state helps introduce an experiment on the effects of warm and cool water on ice. The teacher gives each student a cup of warm water and a cup of cool water, and asks them to describe the water temperature and make predictions about which cup of water will melt ice more quickly. The students then test their predictions by placing an ice cube in each cup, observing and describing what they see. The teacher guides their reflections on the state changes they observe, eliciting students' articulations of the change from solid to liquid. Follow-up activities provide for additional observation and experimentation with ice and whether different materials change their state when exposed to freezing temperatures.

Figure 1. Sample activity instructions, MTP-Math

March-Math-W4-A2 | **Volume 1** | Small Group

GET READY

Objectives
- Use simple tools (condiment cups) to measure, compare, and order the volume of up to 3 objects

Use the Lingo
- Measure
- Compare
- Order
- Volume
- Counting

Materials:
- Plastic containers of varying shapes, sizes, and volumes (4 per small group)
- Bowl of uncooked rice
- Condiment cups
- Paper
- Pen

Preparation:
- N/A

ENGAGE

1. Math chant.
2. Ask: *Today we are going to learn about volume. Volume means "how much something can hold." I am going to need your help to figure out how much each one of these containers can hold. Can you help me?*

INVESTIGATE

3. Work with the students to fill 3 of the jars.
   - Practice filling plastic containers with the students counting the number of condiment cups it takes. (It's important to level off the condiment cups to put in the same amount each time.
   - Write down how much each jar holds.
   - Talk about how the jar with a greatest volume is going to be the one that holds the most, which means it is going to have the biggest number. It might not look like the tallest or the biggest but it has the largest volume because it holds the most.
4. Have students order the jars from smallest to largest volume.
   - Encourage them to think about the jars in terms of numbers of scoops that they hold.
5. Replace 1 of the containers with another container of different volume. Repeat.

DISCUSS

6. How did we find out which container holds more? Which has the largest volume?
   - *What is volume? Why do you think it matters? How can you use volume?*
   - Pose example scenarios: *If you are really thirsty, are you going to pick the small (Dixie) cup of water, or the big bottle of water? Why? If you have to move all the books from the bookshelf, are you going to need a little box or a big box? Why?*
   - Allow students to attempt to explain volume in their own words but scaffold use of new language and concepts.

EXTEND

- Order all 4 of the containers.
  - Take all 4 of the jars and order them by volume. Make a "mistake" in your ordering and allow the students to correct it.
  - Use other containers to discuss volume: milk carton, juice box, water bottle, etc.

MAKE IT WORK

For Students With More Advanced Skills	For Students Requiring More Support
• Divide students into pairs, and have them predict and fill the containers.	• Use the scoops and rice to order the volume of familiar containers (milk carton, cup for juice, yogurt cup).

Figure 2. Sample activity instructions, MTP-Science

January-Science-W2-A2	**Water and Ice**	Small Group

GET READY

Objectives
- Observe and describe the characteristics of water in liquid and solid (frozen) forms
- Predict, observe, and describe the effects of different temperatures on ice

Use the Lingo
- Liquid
- Solid
- Water
- Ice
- Hard
- Freeze
- Frozen
- Melt
- Warm
- Cold
- Shape
- Container

Materials (Provided; **Not provided**):
- 2 Mini ice cube trays (1 per small group)
- 2 Blank laminated poster boards (1 per small group)
- Red cups (1 per student)
- Blue cups (1 per student)
- 2 blue cup icons (1 per small group)
- 2 red cup icons(1 per small group)
- **Cold water**
- **Warm water**

Preparation:
- Using the mini ice cube tray and water, make tiny ice cubes. You will need at least 3 ice cubes per student.
- Prepare the poster board:
  - Write "Prediction" and "Results" as row headings (left side), with prediction on top and results on the bottom.
  - Attach one blue and one red cup icon as column headings.

ENGAGE

1. Science Chant
2. Explore the ice
   - Give each student a small ice cube and ask the students to describe the ice. Ask: *Is the ice a solid or a liquid?*
   - Let the students suck on their ice cubes. Ask: *What is happening to the ice? What does ice turn into when it melts? Is it still a solid?*
3. *Today we are going to find out how to make our ice melt from a solid to a liquid even faster!*

INVESTIGATE

4. Explore the materials.
   - Give each student a red cup filled halfway with warm water and a blue cup filled halfway with cold water.
   - Ask students to place a finger in the cups and describe how the water in each cup feels.
5. Predict: *In which cup would an ice cube melt more quickly? Why?*
   - In the Prediction row of poster, tally the number of who think the ice in the blue (cold) cup or the red (warm water) cup will melt faster.

INVESTIGATE (Continued)

6. Experiment.
   - Give each student two ice cubes, and ask students to drop an ice cube into each cup at the same time.
   - Ask students to describe what they observe happening to the ice cubes, and to see in which cup the ice melts first.

DISCUSS

7. Analyze results
   - Ask: *In which cup did the ice melt first? Why?*
   - Students compare the results they observed to their predictions.
   - Complete the poster by filling in the Results under the blue and red cups.
8. Ask questions, repeat, build on student comments, and ask more questions.
   - Ask: *What happened to our ice cubes?*
   - Ask: *What happened to the ice in the warm water? What happened to the ice in the cold water?*
   - Ask: *Was the ice a solid or a liquid before we put it in the water? What did the ice turn into after it melted?*
   - Ask: *How is this ice different from ice you see outside? Is it the same shape as the ice you find outside?*

EXTEND

- Use opportunities that arise through the day to explore water & ice.
  - Outside, examine puddles (frozen puddles, if available).
  - Fill a container with water, freeze, and discuss the shape of the ice.
  - Put ice cubes in the water table for students to experiment with.
  - Book area: *The Snowy Day*, by Ezra Jack Keats.
  - Make predictions about whether a variety of materials will freeze. Fill ice trays with variety of materials and place in freezer overnight. Discuss.
  - Place a cup of water outside over night to find out whether it is cold enough outside to make it freeze.

MAKE IT WORK

For Students With More Advanced Skills
- As opportunities arise, draw students' attention to frozen water (e.g., frost on grass) and ask why it is frozen now but not always frozen. Ask:
  How is the temperature outside similar to the temperature of the water in the experiment?
  How does each affect ice?

For Students Requiring More Support
- Repeat experiment to give students additional exposure to language and opportunities to use it to describe observations.

What follows is a description of the design guidelines that evolved as a function of our iterative procedures. For each, we explain the relevant design process and the design understandings that emerged.

Emergent Design Guidelines

Guideline 1: Use seasonal linkages where possible, and a yearlong span of activities to develop concept knowledge and skills in situated contexts. As we revised the curricular objectives and their sequence, we focused on development of concepts and skills as taking place in trajectories across the school year rather than during the discrete topical "units" we had begun with, as we had observed that weeks-long units were limited in their potential for encouraging related conceptual development over time. In so doing, we drew upon authentic events to provide context for knowledge construction and skill acquisition. Students' inquiry explorations were linked, when possible, to the seasons, and to what was happening in the natural world. For example, to help children come to understand the plant life cycle within life science, a sequence of activities are undertaken: In the fall, students explore the environment near their schools and collect and describe seeds as they ripen. In winter, students sort and describe seeds and consider how animals use them as a food source. In early spring, students sprout and examine bean seeds and plant the sprouts. In later spring, students experiment to study the effects of light and water on the plants' growth. As spring progresses, the plants mature, often producing seeds by the end of the school year, completing the lifecycle. Through these seasonally anchored, authentic inquiries, students develop understandings of science they can apply to the world outside their classrooms.

We developed the mathematics activities to offer similar opportunities for development and application of concept knowledge and skills in a developmental progression. In Table 2 we describe the progression in development of measurement concepts and skills across the year.

Guideline 2: Focus on what is most important instead of providing teachers with all possible curricular supports. In our evaluation of the curricular implementation during year one, we observed that teachers did not always follow the complete instructions for our activities, and so missed some of the learning objectives. We considered the feedback teachers provided to us in order to better understand this behavior. A predominant teacher concern was that activity instructions were too long to be reviewed in the preparation time teachers had (teachers' available time and whether they persist in fully reviewing curricular instructions are among several of the interrelated factors that influence whether they use and can learn from materials [Davis & Krajcik, 2005]). We decided to scale back the curricular

Table 2. Measurement Skill Development: Comparing Objects in Length

Activity	Objective	Description
Sept Wk 3 Math Counts – Shapes	Compare 2 objects in length	Students explore properties of circles and squares and compare the lengths of the sides of various shapes. Provides a basic introduction to non-standardized measurement.
Oct Wk 1 Building Triangles and Rectangles	Compare and describe the relative length (longer, shorter, same) of 2 objects	Students advance to shape building, rather than simply describing and identifying, using manipulatives to build and compare rectangles and triangles. Language used to describe relative length.
Nov Wk 1 Ordering by Length	Compare and describe the relative length (longest, shortest, middle, same) of 3 objects	Students use objects throughout the classroom to compare lengths *and* place them in the correct order. This activity introduces a third object to be compared, and challenges students to recall their prior measurement skills.
Jan Wk 2 Measuring With Linking Cubes	Measure the length of 1 object using other standardized objects	Following the reading of *Inch by Inch,* by Leo Lionni, students practice measuring objects using standardized objects (linking cubes). This activity serves as the first introduction to standardized measurement, and emphasizes the importance of using the same starting point when making measurement comparisons.
Feb Wk 2 Monkey Measurement	Measure the length of 2 objects using other standardized objects	Students construct their own monkey rulers (10 units long) and begin to conduct standardized measurements of multiple objects. Students are now incorporating all of the previous non-standardized and standardized measurement skills, as well as using all of the language acquired throughout the year.
Apr Wk 1 Length Comparison	Compare and order 5 objects in length	The activity revisits and builds upon the concepts presented in Nov Wk 1. Students are responsible for measuring a variety of animals (on picture cards) and placing them in order by length. Emphasis is placed on different ways to order, as well as ordinal language such as first, second, third, etc.
May Wk 4 Monkey Measurement Part II	Measure the length of 2 objects using other standardized objects	The culminating measurement activity for the year. Students use the same monkey rulers (from Feb Wk 2) but extend the length of the rulers to 15 units. Throughout the activity, students use comparative language, ordinal vocabulary, and make predictions about the lengths of objects before conducting actual measurements.

supports (some activities were supported with five pages of instructions) to what was most important for successful implementation—what students needed to experience and what would enable teachers to provide these experiences—in a maximum of two pages. We explicitly emphasized an inquiry framework (a modification of the 5E Model, Bybee et al., 2006) in the formatting of all activities, with *Engage, Investigate, Discuss,* and *Extend* forming the core of the activity. Through this organization, we provided direct exposure to key mathematical and scientific concepts and skills and explicitly modeled an inquiry approach across every lesson. A *Structured Inquiry* approach was employed, where teachers pose questions and suggest procedures (Bell, Smetana, & Binns, 2005), and students are actively engaged in inquiries of increasing sophistication across the year. At the beginning of the year, students conduct observations and describe what they observe; by the end of the year students are making predictions about what they'll find before going on to conduct observations, then recording their observations as data, analyzing these data, and discussing their findings. Among the benefits of this focused approach on inquiry is that teachers and children have the opportunity to employ mathematics, language, and literacy skills in authentic ways (Gerde, Schachter, & Wasik, 2013; we would of course include science in these pursuits).

Guideline 3: Teachers need explicit support for encouraging student reflection. We observed teachers spending little time encouraging students' reflection when implementing initial versions of our activities. Other researchers have also found that "cognitively challenging talk is somewhat infrequent in the early childhood setting" (Massey, 2004, p. 228). Through our inquiry framework, we provided examples of open-ended questions for teachers' use—questions to which a number of different answers are acceptable and which do not constrain students' responses (de Rivera, Girolametto, Greenberg, & Weitzman, 2005; Hargreaves, 1984). As we summarize elsewhere (Lee & Kinzie, 2012), open-ended questions are thought to encourage higher-order thinking and support students' inquiry, and in fact, teachers' open-ended questions have been found to help children develop abstract language skills involving prediction, analysis, and inference (Wasik, Bond, & Hineman, 2006). Through all *MTP-M/S* activities, teachers expressly cultivate children's thinking with scaffolded questioning. We observed that when teachers' questions were open-ended, students responded with a more varied vocabulary and more complex sentence structures (Lee, Kinzie, & Whittaker, 2012), important for language development and metacognition (see Guideline 4, below).

We also placed emphasis on offering multiple extension options across the classroom day (see *Extend* in Figures 1 and 2 for examples), enabling students to experience and reflect upon the same targeted concepts in different ways (French, 2004). We developed monthly letters for parents that describe what students are learning and suggest everyday activities that can reinforce students' exploration and reflection; this support is particularly important as research suggests that parents may be willing to help their preschool-aged children to learn mathematics, but that they do so less often than for language development, in part because they feel less capable of helping their children learn mathematics (Cannon & Ginsburg, 2008). In addition, we asked teachers to implement an adaptation of a mathematics or science activity during "center time," providing teachers an opportunity to encourage students' reflection, concept development, and use of skills in a smaller group context. Finally, *Make It Work* adaptations offered teachers ways to differentiate these learning activities to help students with varying needs develop concept knowledge and skills. Figures 1 and 2 depict a sample activity including these components.

Guideline 4: To encourage metacognition, children need support for language development. Ginsburg and colleagues (Ginsburg, Lee, & Boyd, 2008) describe the importance of children's language development to facilitate expression of thought. Ginsburg has observed that "*mathematics equals thinking plus language"* (2010). Similarly, Gelman and Brenneman (2004) assert that "science involves not just 'doing' but thinking and talking about the work being done" (p. 156). For children from lower SES backgrounds, support for such language development and use is especially important as they have been found to have developed smaller vocabularies (Fish & Pinkerman, 2003; Hart & Risley, 1995). This limited vocabulary may detract from preschool students' "metacognitive ability to describe one's thinking" (Pappas, Ginsburg, & Jiang, 2003, p. 432). In addition, the amount of preschool teachers' mathematics-related talk has been found to significantly predict the growth of mathematics knowledge in their students (Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006). As a consequence, and in response to teachers' requests, we devoted substantial attention to the modeling and eliciting of mathematical and science language in the context of learning. Every activity highlights specific vocabulary to emphasize, and offers many opportunities for modeling and eliciting in the observations, skill applications, and reflective discussions of findings.

Guideline 5: Children's texts can offer teachers explicit support for introducing key concepts. We observed that teachers sometimes struggled to provide explanations of key science constructs. In response, we purposefully selected children's texts to help teachers introduce new or complex concepts and to guide the inquiry process, as suggested by the NRC (2006), and Sackes, Trundle, and Fevares (2009). Books have been found to offer important scaffolding and productive jumping-off points for later inquiry in research on science learning by primary grade students (Hapgood, Magnusson, & Palincsar, 2004). Casey, Erkut, Ceder, and Young (2008) found that kindergarten students from a low-income urban community showed significantly greater learning of geometry skills when they learned in the context of an engaging adventure story.

Book readings and associated discussions make it possible for teachers to offer conceptual overviews and shared experiences on which to build (for example, a read-aloud of *Bugs Are Insects* [Rockwell, 2001] precedes activities in which children use hand lenses for close examination of insects supplied to classrooms and discovered during nature walks). Even when books are not explicitly about mathematics or science, we recommend ways teachers can aim the discussions toward key mathematics and science concepts and skills. As Ginsburg (2009) notes: "In almost every storybook . . . there are important mathematical ideas." Across the year we employ over 45 mathematics- and science-related texts suitable for prekindergarten, which support mathematics and science learning as well as the development of students' pre-literacy and language skills.

With such curricular design, teachers are offered substantial resources in support of their teaching practice in the context of the curricula themselves. While newer teachers in particular need and want these well-developed curricular supports (Kauffman et al., 2002), in this era of standards-based educational reform and in particular in the domain of early childhood mathematics and science education (where teacher supports are known to be limited [Bowman et al., 2001]), we assert that any pre-K teacher would benefit from such research-based curricula. We now turn our attention to our final research question, presenting data on teachers' implementation of and satisfaction with the curricula.

RESEARCH QUESTION 4: DO TEACHERS IMPLEMENT THE CURRICULA WITH HIGH FIDELITY AND REPORT THAT IT IS USEFUL TO THEIR PRACTICE? IS FIDELITY OF IMPLEMENTATION RELATED TO CHILD OUTCOMES?

The results of large-scale national studies indicate that there are challenges with early childhood curricular implementation quality and fidelity (Pianta et al., 2005). Even when offered validated curricula, pre-K teachers often struggle to implement them with high quality and fidelity, largely as a function of their lack of content knowledge and confidence (Pianta et al., 2005). In his Curriculum Research Framework (CRF), Clements (2007) recommends that proposed curricula be examined via a series of small-scale research studies, in order to help identify and improve modes of delivery that encourage and support teachers' fidelity to the curricula.

This initiative, in turn, can be associated with student learning outcomes, where teachers who exhibit higher fidelity to a successful curriculum help to produce greater student gains.

In order to examine teachers' engagement with the curricula and the influence of that engagement on child outcomes, we conducted a small implementation test. We assessed four main aspects of fidelity: adherence, dosage, quality of delivery, and participant responsiveness (Dane & Schneider, 1998; Domitrovich & Greenberg, 2000). *Adherence* refers the degree to which a curriculum or intervention is delivered as prescribed. *Dosage* refers to the duration and frequency of administration of curricula. *Quality of delivery* refers to the qualitative or affective components of implementation. *Participant responsiveness* assesses the degree to which teachers are supportive of the curriculum.

CURRICULAR TEST PARTICIPANTS

For this implementation test, we invited two moderately sized school districts in a mid-Atlantic state (ProximityOne, 2013) to participate in a yearlong trial of the *MTP-M/S* curricula. District personnel distributed our request for teacher volunteers; the research team was contacted only by teachers willing to participate. Eight pre-kindergarten teachers responded, and we distributed corresponding invitation and consent forms to the parents/caregivers of all students in the classroom. After applying our exclusion criteria (students having an Individualized Education Plan in any area other than speech, or who were of limited English proficiency were excluded), we randomly selected eight students per classroom (n = 64 total) to participate in the direct assessments. Teachers received the yearlong *MTP-M/S* curricula and all corresponding curricular materials. All teachers taught in classrooms that included students with one or more risk factors for later school failure (poverty, second language learners, or health or developmental problems).

Teachers were all female and ranged in age from 24 years to 58 years (M = 40.88, SD = 12.25). Teachers reported their race/ethnicity as Caucasian (75%) or African American (25%). They held an average of 13 years of experience working with children (SD = 11.46) and all held at least a bachelor's degree (38% had a degree in Early Childhood Education). Each teacher served between 16 and 18 children and was supported by a full-time teaching assistant.

The students (48% female) ranged in age from 4 to 5.11 years (M = 4.49, SD = .29). Fifty-six percent of students were Caucasian, 36% were African American, and 8% were other races or ethnicities. The sample was predominantly low income; the average income-to-needs ratio (computed by taking the family income, exclusive of federal aid, and dividing it by the federal poverty threshold for that family) was 1.6 (*SD* = 1.1) with 30% of households having ratios lower than one (below the poverty line) and 70% of families having ratios lower than two. About half of students' mothers had a high-school education or less (48%), 34% had some college or technical assistance, but no degree, and the remaining 18% had a two- or four-year degree. Twelve percent of parents reported that their student had a disability. The teachers and parents/caregivers consented to research participation, using protocol approved by our Institutional Review Board for protection of human subjects.

PROCEDURES

Teachers implemented *MTP-M/S* curricular activities five times per week (two mathematics and two science activities, along with one mathematics *or* science center-time activity). The activities ranged from 10–25 minutes in duration. As part of their participation, teachers were asked to videotape their implementation of all *MTP-M/S* activities, as previously described for the preceding curricular evaluations.

In fall and again in spring, we administered two direct assessments of children's mathematics knowledge/skill (see description of Measures, below). Of the original children who completed pre-test assessments, 91% (58 out of 64 children) completed post-test assessments. As the science measures were under development in the fall and winter of year two, these measures were administered at post-test only. The fall assessments were conducted in mid-October, approximately six weeks after the start of the school year, in order to enable teachers to establish classroom routines and provide a period of acclimatization for students who were new to the school experience. Approximately 20 weeks after completion of the fall assessments (in April–May), the spring assessments were administered.

Coding of Videotapes

Videotapes (n = 112) were selected to provide equal representation of mathematics and science activities across months (September–April), randomly drawn from the tapes submitted by each teacher (M = 14 tapes/teacher). Selected tapes were coded two times, each time for a different construct. The first coding focused on that aspect of fidelity that was teachers' adherence to the *MTP-M/S* lessons. Twenty percent of these tapes were double coded for adherence by a "master" coder, in order to calculate reliability. To determine inter-rater reliability we calculated the intraclass correlation coefficient (ICC) for the total score of all items and found that there was good inter-rater agreement (ICC = .89). The second coding focused on another aspect of teaching fidelity, the quality of teacher–child interactions in the classroom, using the *Classroom Assessment Scoring System* (CLASS). All CLASS coding was conducted by a group of trained and reliable coders (scoring within one point for each dimension on at least 80% of the codes).

MEASURES

Teachers' Implementation Fidelity

Adherence to the curricula. The *MTP-M/S* fidelity measure was developed to assess teachers' adherence to the *MTP-M/S* curricular design, to help us determine the extent to which the learning experiences children received were in alignment with what we intended. The fidelity measure contained 12 items, including items such as, "Teacher actively models the use of mathematical and/or scientific language," and "Children perform the activity tasks specified in the lesson plan." Upon conclusion of coding, the items were weighted so that all items were on a three-point scale. Dichotomous items were score 0 for "no" and 2 for "yes." Ordinal items were scored 0 for "none" or "some" (combined due to lack of variability), 1 for "most," and 2 for "all." A total score was calculated by summing the 12 items for a total possible score of 24. The final measure was found to have good internal consistency ($\alpha = .73$).

Dosage. Teachers were asked to videotape all *MTP-M/*S activities they implemented. The curricular dosage that students received was therefore determined based on the number of activity videotapes that teachers submitted. In all, teachers could have submitted 132 tapes (66 mathematics and 66 science) across the span of the year.

Quality of instruction. We assessed the quality of teacher–child interactions by coding each tape using the *Classroom Assessment Scoring System—Pre-K* (CLASS; Pianta et al., 2008). The CLASS is an observational measure that reflects 10 dimensions across three primary domains of Emotional Support, Classroom Organization, and Instructional Support. Each dimension is scored using a seven-point scale that ranges from low (1, 2 points) to high (6, 7 points). Research on the CLASS has indicated that higher CLASS ratings are correlated with greater child gains in academic achievement and social competence (Mashburn et al., 2008). After coding was completed for this study, an average score for each domain was created for each teacher, with a possible range of 1 to 7. Because our study is focused on increasing the quality of teachers' Instructional Support, this is the domain that we used in our subsequent analyses.

Participant responsiveness. At the end of the school year, teachers completed seven survey items intended to reflect their attitudes about the *MTP-M/S* curricula. Teachers responded with "agree" or "disagree" to items such as: *MTP* Math and Science Activities were "*. . . a valuable addition to my teaching practice,*" "*. . . more useful to me as a teacher than other early childhood math and science curricula,*" and "*. . . promoted skills that the children in my classroom needed.*"

Direct Child Assessments

Number sense and operations. The *Test of Early Mathematics Ability, Third Edition* (TEMA-3) (Ginsburg & Baroody, 2003) was used to assess students' skills in number sense and operations. The TEMA-3 is designed to be given to children between the ages of 3 years, 0 months, and 8 years, 11 months, as either a diagnostic tool for children having difficulty in a specific mathematics domain or to determine how a child is performing in relation to his or her peers. The examiner begins testing using an item that has been determined for the examinee based on the respondent's chronological age in years, and then a basal and ceiling are established to calculate a raw score. The TEMA-3 is a norm-referenced, reliable, and valid test, yielding a single score reflecting children's early mathematical ability (Ginsburg & Baroody, 2003; Klein et al., 2002), which showed good internal consistency in this implementation ($\alpha = .92$).

Geometry and measurement. The *Geometry and Measurement Assessment* (GMA) we employed is a derivative of the *Tools for Early Assessment of Mathematics* (TEAM; Clements, Sarama, & Liu, 2008). Eleven TEAM items were retained intact, six questions were developed as extensions of questions in the TEAM (for example with the TEAM, items direct children to make a triangle and a rectangle using coffee stirrers; we added an item for making a square), and 13 new items were developed to address curricular objectives not assessed in the TEAM (for example, identifying a square by name and describing how the child knew it was a square). The resulting 30-item measure took approximately 20 minutes to administer. A single raw score was determined for each child based on the number of correct responses; possible scores range from 0 to 50. Internal reliability in our administration was high ($\alpha = .87$).

Because direct assessments of science knowledge and skill that were suitable for pre-K administration were not available at the time of this trial, the research team needed to develop these assessments. Given that they were administered only at years' end, they are not included here.

DATA ANALYSES

Descriptive analyses were performed to determine teachers' fidelity to and satisfaction with the curricula. To explore the associations between adherence, dosage, and quality of instructional interactions, and students' mathematics outcomes, we fit two-level HLM models that accounted for the nesting of students within teachers. The resulting data structure involved an average of eight children in each of the eight teachers' classes. Data were analyzed using Mplus Version 6.1 (Muthen & Muthen, 1997–2010). Analyses were run using maximum likelihood estimation with robust standard errors so that data analyses used all available data from all students who were selected for the direct assessments across the classrooms.

We fit models examining the associations between adherence, dosage, and quality of instructional interactions, and each of the two mathematics outcomes (TEMA-3 and GMA). The level-1 model specifies that children's spring mathematics assessment is a function of their fall pretest score on this assessment. In the level-2 model, teachers' adherence to the curricula, dosage, and quality of instructional interactions were entered. The magnitude and direction of the coefficients indicates the association between children's development of mathematics skills and their teacher's adherence to the curricula, dosage, and quality of instructional interactions.

RESULTS

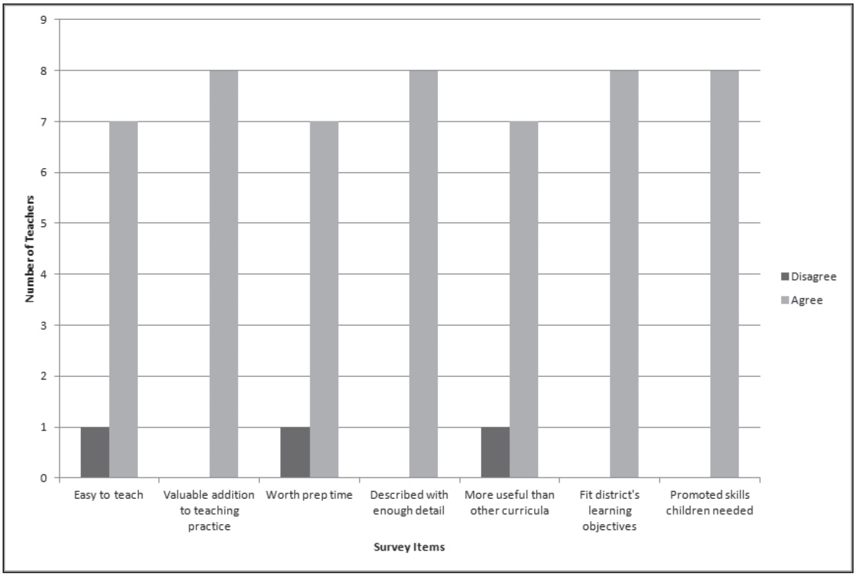
Do teachers implement the curricula with high fidelity? Table 3 provides descriptive information about teachers' adherence to the curricula. Overall, teachers showed fairly high adherence, as assessed by our fidelity measure. Across activities, out of a possible total of 24 points, teachers scored an average of 14.89 points (SD = 2.65). In examining the distribution on each fidelity item, the majority of teachers got scores of "yes" on the dichotomous items and scores of "most" or "all" on the ordinal items. Teachers implemented an average of 84 lessons (range = 30–127, SD = 35.78). This represents an implementation of over 60% of the curricular activities, with some teachers implementing as many as 96% of the curricular activities. In the area of teaching quality, teachers' mean score on the Instructional Support domain of the CLASS measure was over half a point higher than the average Instructional Support scores reported in a large multi-state pre-kindergarten study ($M = 3.20$ [$SD = .57$] vs. $M = 2.47$ [$SD = 1.10$]) (Pianta et al., 2005).

Table 3. Fidelity to *MTP-M/S Curricula* Implementation Trial Teachers

	n	*M*	*SD*	Range
Implementation Fidelity				
Total Adherence – Observed	8	14.89	2.65	10.83 – 18.85
Dosage – Number of Activities	8	83.88	35.78	30.00 – 127.00
Quality of Instruction	8	3.20	.57	2.56 – 4.42

Figure 3 depicts teacher responses to the survey on their satisfaction with the *MTP-M/S* curricula. All teachers agreed that *MTP-M/S* was a valuable addition to their teaching practice, that the lessons were described in enough detail to implement, fit the district's learning objectives, and promoted the skills that children needed. Seven out of eight teachers also agreed that the curricula were easy to teach, activities were worth the prep time, and were more useful than other curricula.

Figure 3. Teacher survey results: attitudes toward *MTP-M/S*



Is teacher fidelity of implementation associated with children's mathematics skills? Table 4 provides data on the relationship between teachers' curricular adherence, dosage, and quality of instruction, and students' mathematics skills. Students' pre-test scores significantly predicted their post-test scores for both number sense and operations, and geometry and measurement. Adherence to the *MTP-M/S* curricula was associated with significant gains from fall to spring in number sense and operations, as measured by the TEMA (B = .60, $p < .01$), and significant gains in geometry and measurement, as measured by the GMA (B = .42, $p < .01$). Curricular dosage students received was significantly associated with gains in geometry and measurement (B = .05, $p < .01$), but not with number sense and operations. Conversely, quality of instruction was significantly related to gains in number sense and operations (B = 1.39, $p < .05$), but not geometry and measurement.

Table 4. Associations Between Curricular Adherence, Quality of Instruction, and Dosage and Students' Mathematics Skills

	TEMA-3 (Number Sense & Operations)		GMA (Geometry & Measurement)	
	B	***SE***	**B**	***SE***
Level-1				
Pre-test	1.09**	0.24	0.73**	0.05
Level-2				
Curricular adherence	0.60**	0.23	0.42**	0.17
Dosage	0.00	0.02	0.05**	0.01
Quality of instruction	1.39*	0.60	0.71	1.18

**p ≤ .01, *p ≤ .05, †

DISCUSSION: WHAT WAS LEARNED FROM RESEARCH ON CURRICULAR DEVELOPMENT FOR PRE-KINDERGARTEN MATHEMATICS AND SCIENCE

A research-based process to develop high-quality curricula to support development of young children's mathematics and science knowledge and skills is important in laying the foundations for later educational success, particularly for children at risk for early school failure (Bowman et al., 2001; NMAP, 2008). While some curricula supporting early mathematics and science learning have shown promise, large-scale studies suggest that high-quality curricula alone may be insufficient to favorably impact teacher practices and child outcomes (Pianta et al., 2005). Fidelity of teachers' curricular implementation, including both adherence and quality, is critical for optimal instructional effectiveness. This is especially true for children served in schools of lower socio-economic status (LoCasale-Crouch et al., 2007; Nye, Konstantopoulos, & Hedges, 2004). In these schools, teachers have been found to receive less preparation, and to report both lower confidence in their ability to influence student learning, and lower expectations for student success (see the research synthesis offered by Santagata, 2009).

The methodology for research on curriculum development promises two important outcomes (Clements, 2004, 2007): First, the design of the curricular content, structure, and activities can be guided by existing theory and research, as well as informed by purposeful testing undertaken in a progressively expanding series of evaluations. Second, the products of this endeavor can include not only complete curricula but also result in emergent guidelines that can inform the design of other curricula.

Such curricular development is especially important when undertaken to address student "opportunity gaps" in order to determine designs that will support under-served students who may otherwise under-perform (Gutierrez, 2008) as well as scaffold teachers' curricular enactment (Ball & Cohen, 1996).

In this study, the application of RCD methods has enabled effective development of mathematics and science curricula for students potentially at risk for early school failure, an especially important undertaking given the importance of early mathematics and science knowledge and skill for predicting later academic success (Claessens & Engel, 2013; Duncan et al., 2007; Grissmer et al., 2010; NMAP, 2008). The RCD model ensured our identification of the most important concepts and skills to be targeted in order to meet the needs of these children. The RCD frame explicitly demanded we further reap the benefits of a theoretical and research-based foundation for our activity designs and teacher guidance, in order to: (1) achieve a balance between student-centered and teacher-guided explorations (as suggested by the work of French, 2004; Gelman & Brenneman, 2004; Justice & Pullen, 2003; Kirschner et al., 2006; NMAP, 2008); (2) provide for anchored investigations (Brown, Collins, & Duguid, 1989) as well as intentional teaching (Ginsburg & Ertle, 2008); and (3) support high-quality teacher–child interactions to encourage students' learning and development (Hamre & Pianta, 2007; Mashburn & Pianta, 2006; Rutter & Maughan, 2002).

An interdisciplinary design team ensured that multiple forms of expertise were brought to bear on the curricular designs, including those of mathematics and science education, early childhood education, developmental psychology, and instructional design. As dictated by the RCD frame, the designs were refined through iterative trials in classrooms serving our target population, resulting in curricular improvements and the emergence of design guidelines that can inform similar curricular development efforts. These resulting guidelines offer specific direction for the design of student learning activities:

- Develop students' concept knowledge and skills via a yearlong curricular framework affording seasonal linkages and intentional development over time;
- Support students' metacognition through language development; as well as design for teachers' optimal implementation of the curricula;
- Accommodate teachers' limited preparation time by focusing curricular supports on what is most important for teachers to facilitate and for students to experience;

- Provide teachers with explicit support for encouraging student reflection; and
- Integrate children's texts to provide both teachers and students with an introduction to concepts that offer a critical foundation for later activities.

All of this appears to matter, as this small implementation trial indicated that teachers reported using the curricula fairly often (dosage), were generally observed to follow curricular plans (adherence), and were determined to have implemented the curricula at a high level of quality (teachers' Instructional Support quality was noticeably higher than that reported in a large multi-state pre-kindergarten study [Pianta et al., 2005]). Although the field of implementation science is growing (Halle & Martinez-Beck, 2013), there is still relatively little research connecting fidelity of curricular implementation with student outcomes in early childhood (Hamre et al., 2010). This study adds to a growing body of research suggesting the importance of curricular dosage, adherence, and quality in predicting growth in children's mathematics skills across pre-kindergarten.

Students in classrooms with higher adherence to the curricula made greater gains in both number sense and operations skills and geometry and measurement skills across the year. Teachers in these classrooms tended to implement the activities in their specified format (whole group, small group), and implemented all parts of the activities. This finding is consistent with research suggesting that it is particularly important to ensure curricular adherence when evaluating whether a curriculum has the intended impacts on children's skills (e.g., Clements & Sarama, 2008; Hamre et al., 2010). Indeed, as described by Sarama and Clements (2013), "Without high-fidelity implementation, few positive results can be realized. One cannot even know if the intervention *could* have been effective or not" (p. 175).

We also found that children in classrooms where a greater number of curricular activities were implemented showed greater gains in geometry and measurement across the year. These may be mathematics domains in which the MTP-Math curriculum offers particularly strong support for instruction. These are also areas where teachers have had few experiences in their own education or professional development (NRC, 2009), and are typically less emphasized in teachers' classrooms (e.g., Kinzie et al., 2014). In contrast to geometry and measurement, we found that curricular dosage was not associated with gains in children's number sense and operations skills. Research suggests that teachers may be more comfortable implementing content in this mathematics subdomain, and that this is the math subdomain that is covered with popular comprehensive curricula (e.g., Creative Curriculum, High Scope). A comparison of the percentage of MTP-M/S activities with activities implemented by teachers using Creative Curriculum and High Scope found that there were similar proportions of number sense activities, but that the MTP-M/S curriculum offered a greater percentage of activities than those implemented by teachers using Creative Curriculum or High Scope in the area of geometry and measurement (Kinzie et al., 2014).

Finally, we also found that higher quality of delivery was related to gains in number sense and operations. This finding is consistent with other research suggesting that quality of the mathematics environment is related to children's math outcomes (Clements & Sarama, 2008). Surprisingly, we did not find the association between quality of delivery and gains in geometry and measurement across the year. It could be that this is a math subdomain for which it is sufficient for teachers to implement effective activities and see resulting gains in children's learning (as might be suggested by the association between curricular adherence dosage and children's gains in geometry and number sense). Alternatively, the lack of a significant association between quality of instructional interactions and children's gains in geometry and measurement may be due to the lack of sensitivity of the CLASS to detect differences in the quality of specific aspects of mathematics-related instruction. Another measure that is more sensitive to differences in the quality of mathematics instruction (e.g., the Classroom Observation of Early Mathematics, Sarama & Clements, 2007) might be more likely to be related to children's mathematics outcomes across mathematics subdomains.

LIMITATIONS

There are several limitations associated with the results described here that are worthy of note. We were unable to test the associations between teachers' fidelity of curricular implementation and students' learning in science. This was due to the lack of validated measures suitable for assessing science learning at the pre-kindergarten level. While the research team developed science assessments for this purpose, they were not available until the end of the implementation trial and so results are not included here. Additionally, the implementation trial was not designed to test the impact of the curricula on students' learning, which would have required a randomized trial comparing effects of the curricula in the intervention group to those obtained by a control group.

We intentionally chose mathematics and science as content areas on which to focus our curricula. We selected these domains because they can promote children's critical thinking skills (e.g., Klahr et al., 2011), and because early knowledge and skills in math and science are foundational for subsequent learning across domains (Grissmer et al., 2010; NMAP, 2008; Sarama et al., 2012; Weiland et al., 2011). Initial studies of mathematics-focused curricular interventions have suggested that high-quality implementation of these curricula are associated with gains not only in math, but also in children's language, executive function, and emotional development (Sarama et al., 2012; Weiland et al., 2011). As noted above, we based our curricula on effective teacher–child interactions important across domains, and developed activities that incorporated other subject areas. For these reasons, we hope that implementation of our curricula will be associated with gains in other important areas of children's development such as critical thinking, language, and executive function (e.g., inhibitory control, working memory, and cognitive flexibility). However, a limitation of this study is that we did not assess children's skills across subject areas. In future studies, it will be important to determine whether the implementation of *MTP-M/S* mathematics and science curricula are associated with gains in foundational thinking skills and in other domains.

Regarding teachers' participation, there are several potential limitations. Most obviously, different results may have been obtained were curricular implementation mandated, rather than adopted by willing teacher volunteers. The videotaping of teachers' practice may also have introduced limitations. First, teachers being videotaped may have exhibited a different practice than when not being observed in this or other ways. However, since teachers routinely videotaped all of their *MTP-M/S* implementations, they reported that they and their students became used to the recordings, so it is possible that any such influences attenuated over time. In addition, while videotapes of teachers' practice have been used in other studies to establish various aspects of teachers' implementation fidelity (e.g., Pianta, Mashburn, Downer, Hamre, & Justice, 2008), we acknowledge that teachers' dosage data (the numbers of videotapes submitted) may have been influenced in part by their self-perceptions of adherence and quality. This may have been the case for teachers who felt more prepared to facilitate an activity and/or who always videotaped their activities, or who felt they implemented activities with high quality, feeling more comfortable submitting a larger number of videotapes and demonstrating greater dosage. Therefore, it may be that some teachers implemented more of the curriculum than their submitted tapes reflected.

Finally, a limitation of this research is that it cannot determine the lasting benefits of curricular usage, undertaken as it was during the earliest stages of the curriculum development process. Additional research will be needed to ascertain whether effects noted over the short term will be sufficiently robust to positively support students as they move through their educational experiences in later years.

IMPLICATIONS

This line of inquiry serves as a demonstration of the potential offered by the RCD model: curricula that can be implemented with quality and fidelity, and which positively influence student learning, along with the evolution of design understandings and principles useful in guiding future curricular development. Such curricular design offers teachers substantial resources in support of their teaching practice, particularly important in this era of standards-based educational reform. Additionally, research-based curricular supports are especially critical given (1) high rates of new teachers entering the workforce (in part due to attrition—annual turnover reports range from 17%-20%; NEA Today, 2008) and (2) for pre-kindergarten, the anticipated need for increasing numbers of new teachers due to anticipated adoptions of universal pre-K (estimated by Clifford and Maxell in 2002 to be over 40,000 new pre-K teachers in the United States by the year 2020). Newer teachers emphatically want these high-quality curricula, and they need them if they are going to be effective and remain in education (Kauffman et al., 2002).

In our current research, we are continuing to examine the effectiveness of the *MTP-M/S* curricula. In this research, we employ a fully randomized model and a larger number of participating classrooms, enabling a more rigorous evaluation of the curricula, as recommended in the expanding cycles of evaluation prescribed by the RCD model (Clements, 2007). In addition, we are extending the curricula with a newly developed teacher support system. In these resources, we feature brief online video demonstrations of high-fidelity implementation of each of the activities, along with short teaching tips for all activities (which emphasize how students come to understand concepts and develop skills, common misconceptions students may develop, and the concepts and skills themselves), and other forms of online support, which extend the educative design of the curricula (Beyer & Davis, 2009; Davis & Krajcik, 2005; Forbes & Davis, 2010). Extensive teacher professional development has been found to lead to improvements in teaching practice (Clements & Sarama, 2008; Yoon, Duncan, Lee, Scarloss, & Shapley, 2007); we are hopeful that delivery of professional development supports via the Internet can increase scalability and accessibility (NRC, 2007), and therefore may be more likely to make a detectible difference in the practice of a large number of teachers. Employing the RCD model while iteratively designing, developing, and evaluating curricular and teacher support resources will help ensure that we, and other developer/researchers, have the best chance of success with these efforts.

REFERENCES

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy: A tool for curriculum reform.* New York, NY: Oxford University Press.

Balfanz, R. (1999). Why do we teach young children so little mathematics? Some historical considerations. In J. V. Copley (Ed.), *Mathematics in the early years.* Reston, VA: National Council of Teachers of Mathematics & National Association for the Education of Young Children.

Ball, D. L., & Cohen, D. K. (1996). Reform by the book: What is—or might be—the role of curriculum materials in teacher learning and instructional reform? *American Education Research Journal, 25*(9), 6–8, 14.

Bell, R. L., Smetana, L., & Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher, 72*(7), 30–33.

Beyer, C. J., & Davis, E. A. (2009). Using educative curriculum materials to support preservice elementary teachers' curricular planning: A comparison between two different forms of support. *Curriculum Inquiry, 39*(5), 679–703.

Bowman, B. T., Donovan, M. S., & Burns, M. S. (2001). *Eager to learn: Educating our preschoolers.* Washington, DC: National Research Council.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32–42.

Brown, J., & Greenfield, D. B. (2010). *E-I-E-I-O: Young scientists are signing a new song.* Paper presented at the Annual Grantee Meeting, Institute of Education Sciences, U.S. Department of Education, Washington, DC.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). *BSCS 5E Instructional Model: Origins, Effectiveness, and Applications.* Colorado Springs, CO: Biological Sciences Curriculum Study (BSCS).

Cannon, J., & Ginsburg, H. P. (2008). "Doing the Math": Maternal beliefs about early mathematics versus language learning. *Early Education and Development, 19*(2), 238–260.

Casey, B., Erkut, S., Ceder, I., & Young, J. M. (2008). Use of a storytelling context to improve girls' and boys' geometry skills in kindergarten. *Journal of Applied Developmental Psychology, 29,* 29–48.

Chalufour, I., & Worth, K. (2003, 2004, 2005). *Young Scientist Series.* St. Paul, MN: Redleaf Press.

Claessens, A., & Engel, M. (2013). How important is where you start? Early mathematics knowledge and later school success. *Teachers College Record, 115*(6), 1–29.

Clements, D. H. (2004). Major themes and recommendations. In D. H. Clements & J. Sarama (Eds.), *Engaging young children in mathematics: Standards for early childhood mathematics education* (pp. 7–72). Mahwah, NJ: Lawrence Erlbaum.

Clements, D. H. (2007). Curriculum research: Toward a framework for "Research-based Curricula." *Journal for Research in Mathematics Education, 38*(1), 35–70.

Clements, D. H., & Sarama, J. (Eds.). (2004). *Engaging young children in mathematics: Standards for early childhood mathematics education.* Mahwah, NJ: Lawrence Erlbaum.

Clements, D. H., & Sarama, J. (2007). *Building Blocks-SRA real math teacher's edition, Grade PreK.* Columbus, OH: SRA/McGraw-Hill.

Clements, D. H., & Sarama, J. (2008). Experimental evaluation of the effects of a research-based preschool mathematics curriculum. *American Education Research Journal, 45*(2), 443–494.

Clements, D. H., Sarama, J., & Liu, X. H. (2008). Development of a measure of early mathematics using the Rasch model: The Research-Based Early Maths Assessment. *Educational Psychology, 28*(4), 457–482.

Clifford, R., & Maxwell, K. (2002). *The need for highly qualified pre-kindergarten teachers.* Paper presented at the Preparing Highly Qualified Preschool Teachers Symposium, Chapel Hill, NC.

Common Core State Standards Initiative. (2012). In the states. Retrieved from http://www.corestandards.org/in-the-states

Curby, T. W., Rimm-Kaufman, S. E., & Ponitz, C. C. (2009). Teacher–child interactions and children's achievement trajectories across kindergarten and first grade. *Journal of Educational Psychology, 101*(4), 912–925.

Dane, A. V., & Schneider, B. H. (1998). Program integrity in primary and early secondary prevention: Are implementation effects out of control? *Clinical Psychology Review, 18*(1), 23–45.

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*(3), 3–14.

de Rivera, C., Girolametto, L., Greenberg, J., & Weitzman, E. (2005). Children's responses to educators' questions in day care play groups. *American Journal of Speech-Language Pathology, 14*(1), 14–26.

Domitrovich, C. E., & Greenberg, M. T. (2000). The study of implementation: Current findings from effective programs for school aged children. *Journal of Educational and Psychological Consultation, 11*, 193–222.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klevanov, P., . . . Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446.

Duncan, G. J., & Magnuson, K. (2013). Investing in preschool programs. *Journal of Economic Perspectives, 27*, 109–132.

Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academies Press.

Early, D., Iruka, I. U., Ritchie, S., Barbarin, O. A., Winn, D.-M. C., Crawford, G. M., . . . Pianta, R. C. (2010). How do pre-kindergarteners spend their time? Gender, ethnicity, and income as predictors of experiences in pre-kindergarten classrooms. *Early Childhood Research Quarterly, 25*, 177–193.

Emmer, E. T., & Stough, L. (2001). Classroom management: A critical part of educational psychology, with implications for teacher education. *Educational Psychologist, 36*(2), 103–112.

Epstein, A. S. (2006). *Numbers plus: A comprehensive approach to early mathematics education.* Washington, DC: Institute of Educational Sciences, U.S. Department of Education.

Ertle, B., Ginsburg, H. P., Cordero, M. I., Curran, T. M., Manlapig, L., & Morgenlander, M. (2008). The essence of early childhood mathematics education and the professional development needed to support it. In A. Dowker (Ed.), *Mathematical difficulties: Psychology and intervention* (pp. 60–84). Amsterdam, The Netherlands: Elsevier.

Fish, M., & Pinkerman, B. (2003). Language skills in low-SES rural Appalachian children: Normative development and individual differences, infancy to preschool. *Applied Developmental Psychology, 23*(5), 539–565.

Forbes, C. T., & Davis, E. A. (2010). Curriculum design for inquiry: Preservice elementary teachers' mobilization and adaptation of science curriculum materials. *Journal of Research in Science Teaching, 47*(7), 820–839.

French, L. A. (2004). Science as the center of a coherent, integrated early childhood curriculum. *Early Childhood Research Quarterly, 19*(1), 138–149.

Gelman, R., & Brenneman, K. (2004). Science learning pathways for young children. *Early Childhood Research Quarterly, 19*(1), 150–158.

Gerde, H. K., Schachter, R. E., & Wasik, B. A. (2013). Using the scientific method to guide learning: An integrated approach to early childhood curriculum. *Early Childhood Education Journal, 41*(5), 315–323.

Ginsburg, H. P. (2009). What is the role of language in children's mathematical thinking? Retrieved from http://www.flvpkonline.org/teachertoolkit/mathThink/teacher/expert.htm

Ginsburg, H. P., & Baroody, A. J. (2003). *Test of early mathematical ability (TEMA-3).* Austin, TX: Pro-Ed.

Ginsburg, H. P., & Ertle, B. (2008). Knowing the mathematics in early childhood mathematics. In O. Saracho & B. Spodek (Eds.), *Contemporary perspectives on mathematics in early childhood education* (pp. 45–65). Charlotte, NC: Information Age Publishing.

Ginsburg, H. P., Greenes, C., & Balfanz, R. (2003). *Big math for little kids: Classroom set.* Dale Seymour.

Ginsburg, H. P., Lee, J. S., & Boyd, J. S. (2008). Mathematics education for young children: What is it and how to promote it. *Social Policy Report, 22*(1), 3–23.

Graham, T. A., Nash, C., & Paul, K. (1997). Young children's exposure to mathematics: The child care context. *Early Childhood Education Journal, 25*(1), 31–38.

Greenes, C., Ginsburg, H. P., & Balfanz, R. (2004). Big math for little kids. *Early Childhood Research Quarterly, 19,* 159–166.

Greenfield, D. B., Jirout, J., Dominguez, X., Greenberg, A., Maier, M., & Fuccillo, J. (2009). Science in the preschool classroom: A programmatic research agenda to improve science. *Early Education and Development, 20*(2), 238–264.

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology, 46*(5), 1008–1017.

Gutierrez, R. (2008). A "gap-gazing" fetish in mathematics education? Problematizing research on the achievement gap. *Journal for Research in Mathematics Education, 39*(4), 357–364.

Halle, T. M. A., & Martinez-Beck, I. (2013). *Applying implementation science in early childhood programs and systems.* Baltimore, MD: Brookes.

Hamre, B. K., Justice, L. M., Pianta, R. C., Kilday, C. R., Sweeney, B., Downer, J. T., & Leach, A. (2010). Implementation fidelity of MyTeachingPartner literacy and language activities: Association with preschoolers' language and literacy growth. *Early Childhood Research Quarterly, 25,* 329–347.

Hamre, B. K., & Pianta, R. C. (2007). Learning opportunities in preschool and early elementary classrooms. In R. C. Pianta, M. J. Cox, & K. L. Snow (Eds.), *School Readiness and the transition to kindergarten in the era of accountability* (pp. 49–83). Baltimore, MD: Brookes.

Hamre, B. K., Pianta, R. C., Mashburn, A. J., & Downer, J. T. (2007). *Building a science of classrooms: Application of the CLASS framework in over 4,000 U.S. early childhood and elementary classrooms.* New York, NY: Foundation for Child Development.

Hapgood, S., Magnusson, S. J., & Palincsar, A. S. (2004). Teacher, text, and experience: A case of young children's scientific inquiry. *Journal of the Learning Sciences, 13*(4), 455–505.

Hargreaves, D. H. (1984). Teachers' questions: Open, closed and half-open. *Educational Researcher, 26*(1), 46–51.

Hart, B., & Risley, T. R. (1995). *Meaningful differences in the everyday experience of young American children.* Baltimore, MD: Brookes.

Hooper, S. R., Roberts, J., Sideris, J., Burchinal, M., & Zeisel, S. (2010). Longitudinal predictors of reading and math trajectories through middle school for African American versus Caucasian students across two samples. *Developmental Psychology, 46*(5), 1018–1029.

Justice, L. M., & Pullen, P. C. (2003). Promising interventions for promoting emergent literacy skills: Three evidence-based approaches. *Topics in Early Childhood Special Education, 23*(3), 99–113.

Kauffman, D., Johnson, S. M., Kardos, S. M., Liu, E., & Peske, H. G. (2002). "Lost at Sea": New teachers' experiences with curriculum and assessment. *Teachers College Record, 104*(2), 273–300.

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*(6), 522–549.

Kinzie, M. B., Cohn, W. F., Julian, M. F., & Knaus, W. A. (2002). A user-centered model for web site design: Needs assessment, user interface design, and rapid prototyping. *Journal of the American Medical Informatics Association, 9*(4), 320–330. doi:10.1197/jamia.M0822

Kinzie, M. B., Vick Whittaker, J., Williford, A., DeCoster, J., McGuire, P., Lee, Y., & Kilday, C.R. (2014). MyTeachingPartner-Math/Science pre-kindergarten curricula and teacher supports: Associations with children's math and science learning. *Early Childhood Research Quarterly, 29*(4), 586–599. doi: 10.1016/ j.ecresq.2014.06.007

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*(2), 75–86.

Klahr, D., Zimmerman, C., & Jirout, J. (2011). Educational interventions to advance children's scientific thinking. *Science, 333*, 971–975.

Klein, A., Starkey, P., & Ramirez, A. (2002). *Pre-K mathematics curriculum.* Glendale, IL: Scott Foresman.

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., & Hedges, L. V. (2006). Preschool children's mathematical knowledge: The effect of teacher "math talk." *Developmental Psychology, 42*(1), 59–69.

Lai, E. (2011). Critical thinking: A literature review. San Antonio, TX: Pearson.

Lee, Y., & Kinzie, M. B. (2012). Teacher questioning and student responses with regard to cognition and language use. *Instructional Science, 40,* 857–874. doi: 10.1007/ s11251-011-9193-2.

Lee, Y., Kinzie, M. B., Whittaker, J. V. (2012). Impact of online support for teachers' open-ended questioning. *Teaching and Teacher Education, 28*, 568–57. doi:10.1016/j. tate.2012.01.002

LoCasale-Crouch, J., Konold, T., Pianta, R. C., Howes, C., Murchinal, M., Bryant, D., . . . Barbarin, O. (2007). Observed classroom quality profiles in state-funded pre-kindergarten programs and associations with teacher, program, and classroom characteristics. *Early Childhood Research Quarterly, 22*, 3–17.

Mashburn, A. J., & Pianta, R. C. (2006). Social relationships and school readiness. *Early Education and Development, 17*(1), 151–176.

Mashburn, A. J., Pianta, R. C., Hamre, B. K., Downer, J. T., Barbarin, O., Bryant, D., . . . Howes, C. (2008). Measures of classroom quality in pre-kindergarten and children's development of academic, language and social skills. *Child Development, 79*, 732–749.

Massey, S. L. (2004). Teacher–child conversation in the preschool classroom. *Early Childhood Education Journal, 31*(4), 227–231.

Muthen, L. K., & Muthen, B. O. (1997–2010). *Mplus user's guide* (6th ed.). Los Angeles, CA: Muthen & Muthen.

National Association for the Education of Young Children [NAEYC] and National Council of Teachers of Mathematics [NCTM]. (2002). *Early childhood mathematics: Promoting good beginnings.* Washington, DC: NAEYC & NCTM.

National Association of State Boards of Education. (2006). *Fulfilling the promise of preschool: The report of the NASBE Study Group on creating high-quality early learning environments*. Alexandria, VA: National Association of State Boards of Education.

National Center for Education Statistics. (2004). *The condition of education 2004*. Washington, DC: Institute of Education Sciences, U.S. Department of Education.

National Center for Education Statistics. (2009). *The condition of education 2009*. Washington, DC: Institute of Education Sciences, U.S. Department of Education.

National Council of Teachers of Mathematics. (2006). *Curriculum focal points for prekindergarten through grade 8 mathematics: A quest for coherence*. Reston, VA: Author.

National Mathematics Advisory Panel. (2008). *Final report of the National Mathematics Advisory Panel*. Washington, DC: U.S. Department of Education. Retrieved from http://www.ed.gov/about/bdscomm/list/mathpanel/report/final-report.pdf.

National Research Council. (2005). *Mathematical and scientific development in early childhood*. Washington, DC: National Academies Press.

National Research Council. (2006). National Science Education Standards. Washington, DC: National Academies Press.

National Research Council. (2007). *Enhancing professional development for teachers: Potential uses of information technology*. Washington, DC: The National Academies Press.

Nye, B., Konstantopoulos, S., & Hedges, L. V. (2004). How large are teacher effects? *Educational Evaluation and Policy Analysis, 26*(3), 237–257.

Pagani, L. S., Fitzpatrick, C., Archambault, I., & Janosz, M. (2010). School readiness and later achievement: A French Canadian replication and extension. *Developmental Psychology, 46*(5), 984–994.

Pappas, S., Ginsburg, H. P., & Jiang, M. (2003). SES differences in young children's metacognition in the context of mathematical problem solving. *Cognitive Development, 18*(3), 431–450.

Pianta, R. C., Belsky, J., Vandergrift, N., Houts, R. M., & Morrison, F. J. (2008). Classroom effects on children's achievement trajectories in elementary school. *American Educational Research Journal, 45*(2), 365–397.

Pianta, R. C., Howes, C., Burchinal, M., Bryant, D., Clifford, R., Early, D., & Barbarin, O. (2005). Features of pre-kindergarten programs, classrooms, and teachers: Do they predict observed classroom quality and child–teacher interactions? *Applied Developmental Science, 9*(3), 144–159.

Pianta, R. C., La Paro, K. M., & Hamre, B. K. (2008). *Classroom Assessment Scoring System (CLASS)*. Baltimore, MD: Brookes.

Pianta, R. C., Mashburn, A. J., Downer, J. T., Hamre, B. K., & Justice, L. (2008). Effects of web-mediated professional development resources on teacher–child interactions in pre-kindergarten classrooms. *Early Childhood Research Quarterly, 23*(4), 431–598.

Preschool Curriculum Evaluation Research Consortium. (2008). *Effects of preschool curriculum programs on school readiness*. Washington, DC: Institute of Education Sciences (IES).

ProximityOne. (2013). *American Community Survey Data Access & Use*. Retrieved March 27, 2013, from http://proximityone.com/acs.htm

Rockwell, A. (2001). *Bugs are insects*. New York, NY: HarperCollins.

Rutter, M., & Maughan, B. (2002). School effectiveness findings, 1979–2002. *Journal of School Psychology, 40*(6), 451–475.

Sackes, M., Trundle, K. C., & Flevares, L. M. (2009). Using children's literature to teach standard-based science concepts in early years. *Early Childhood Education Journal, 36*(5), 415–422.

Santagata, R. (2009). Designing video-based professional development for mathematics teachers in low-performing schools. *Journal of Teacher Education, 60*, 38–51.

Sarama, J., & Clements, D. H. (2007). *Manual for classroom observation* (COEMET), version 3. Buffalo, NY: Research and Assessment Center.

Sarama, J., & Clements, D. H. (2013). Lessons learned in the implementation of the TRIAD scale-up model: Teaching early mathematics with trajectories and technologies. In T. G. Halle, A. J. Metz, & I. Martinez-Beck (Eds.), *Applying implementation science in early childhood programs and systems* (pp. 173–191). Baltimore, MD: Brookes.

Sarama, J., Lange, A., Clements, D. H., & Wolfe, C. B. (2012). The impacts of an early mathematics curriculum on emerging literacy and language. *Early Childhood Research Quarterly, 27,* 489–502. doi:10.1016/j.ecresq.2011.12.002

Schweinhart, L. J., Montie, J., Xiang, Z., Barnett, W. S., Belfield, O. R., & Nores, M. (2005). Lifetime effects: The High/Scope Perry Preschool Study through age 40. *Monographs of the High/Scope Educational Research Foundation, 14.* Ypsilanti, MI: High/Scope Press.

Smith, M. K. (1996, 2000). Curriculum theory and practice. *The Encyclopedia of Informal Education.* Retrieved November 3, 2011, from www.infed.org/biblio/b-curric.htm

Snow, K. (2011). Debunking the play vs. learning dichotomy. In Center for Applied Research (Ed.), *Research news you can use.* New York, NY: National Association for the Education of Young Children (NAEYC).

Soar, R., & Soar, R. (1979). Emotional climate and management. In P. Peterson & H. Walberg (Eds.), *Research on teaching: Concepts, findings and implications* (pp. 97–119). Berkeley, CA: McCutchan.

Stipek, D. (2008). The price of inattention to mathematics in early childhood education is too great. *Society for Research in Child Development Social Policy Report, 22*, 13.

Tu, T. (2006). Preschool science environment: What is available in a preschool classroom? *Early Childhood Education Journal, 33*(4), 245–251.

Wasik, B. A., Bond, M. A., & Hineman, A. (2006). The effects of a language and literacy intervention on head start children and teachers. *Journal of Educational Pyschology, 98*(1), 63–74.

Weiland, C., Eidelman, H., & Yoshikawa, H. (2011). *A regression discontinuity analysis of the impact of Building Blocks in an urban public prekindergarten program and associations between fidelity-to-curriculum and child outcomes.* Paper presented at the annual meeting of the Society for Research on Educational Effectiveness.

Yoon, K. S., Duncan, T., Lee, S. W.-Y., Scarloss, B., & Shapley, K. L. (2007). *Reviewing the evidence on how teacher professional development affects student achievement.* Washington, DC: National Center for Educational Evaluation and Regional Assistance, Institute of Education Sciences, U.S. Department of Education.

MABLE B. KINZIE is Professor of Instructional Technology at the Curry School of Education and Faculty Affiliate at the Center for Advanced Study of Teaching & Learning (CASTL), University of Virginia. She conducts research on theoretically informed, user-centered interactive and instructional design, and has been recognized with awards for scholarship, instructional design, and faculty practice.

JESSICA VICK WHITTAKER is a Research Assistant Professor with the Center for Advanced Study of Teaching and Learning at the Curry School of Education, University of Virginia. Her research focuses on understanding the relation between early teacher–child relationships and children's academic and social-emotional outcomes, and developing and evaluating professional development aimed at improving teacher–child relationship quality.

PAT MCGUIRE is an Assistant Professor in the Department of Curriculum & Instruction at the University of Colorado at Colorado Springs. His research and recent publications focus on early childhood mathematics and intelligent tutoring systems. He holds a PhD in Instructional Technology from the University of Virginia.

YOUNGJU LEE earned her doctoral degree at the University of Virginia with a focus on Instructional Technology. She is now an Assistant Professor in the Department of Education at the Korea National University of Education. Her research interests include technology use for teacher education, online course dropout, and peer interactions.

CAROLYN KILDAY is the Data Administrator for the *MyTeachingPartner-Math/Science* project in the Center for the Advanced Study of Teaching and Learning (CASTL) at the University of Virginia. Her research interests include children's development of mathematical knowledge in preschool and associations between mathematical knowledge and executive function.