Instructional Materials to Support the Next Generation Science Standards: Results of a Proof-of-Concept Study

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Abstract

The problem of how to improve elementary student science achievement in the United States is multi-faceted. To be effective, interventions must consider challenges associated with teaching, learning, and implementing instructional changes at a large scale. In this paper, we present findings from a study of an educative curriculum materials-based intervention that has three central design principles: 1) the materials are aligned with current knowledge about how people learn; 2) the educative components support teacher content and pedagogical content knowledge, and facilitate instructional implementation; and 3) the instructional activities use low-cost, readily available materials amenable to large-scale implementation. Our findings indicate that student learning gains are greater in classes where teachers implement the intervention than in comparison classes. In addition, the extent of materials implementation and fidelity to the pedagogical approach embodied in the materials are positively associated with student achievement gains. Implications of these findings for supporting implementation of the Next Generation Science Standards are discussed.

Instructional Materials to Support the Next Generation Science Standards:
Results of a Proof-of-Concept Study

Science educators and researchers in the U.S. have long recognized that greater coherence in the K–12 science education system is necessary to improve student achievement in science. Toward this goal, the National Resource Council (NRC), National Science Teachers Association, American Association for the Advancement of Science, and Achieve (a non-profit educational organization) are developing the Next Generation Science Standards (NGSS)—a set of K–12 science education standards for nationwide adoption, similar to the Common Core standards in Reading and Mathematics (National Governors Association, 2010; National Resource Center, 2011). Presently, 26 states will consider adopting the NGSS as the science content and practices students will be expected to know and be able to do at various points in their education (Achieve, 2013). However, how teachers should support students in acquiring this set of knowledge and skills is not well defined.

Research has identified principles and practices of effective science teaching that can inform how teachers support students in achieving NGSS learning goals (NRC, 2011; NRC, 2005, NRC, 2000). Research syntheses strongly suggest that learning in science occurs when students play a central and active role in constructing their own understandings of science concepts by building upon what they know and have experienced (NRC, 2000) and engaging in learning opportunities that are relevant to their own lives (Schroeder, Scott, Tolson, Huang, & Lee, 2007). Initially, learners consider their own prior knowledge and ideas about a science topic or phenomenon in the context of a familiar scenario. Subsequent encounters with conceptually related phenomena, particularly those that challenge the learner's current conceptual understanding (Fensham & Kass, 1988), establish the need for learners to adjust their cognitive frame to account for what their current understanding cannot reasonably explain

(Posner, Strike, Hewson, & Gertzog, 1982). With the teacher's guidance, students consider data generated through engagement with phenomena as evidence to develop and support robust explanations for what they observe. Applying an evidence-based explanation to other, related phenomena reinforces scientifically accepted ideas.

There are striking parallels between the way scientists practice science and the way students learn science via a learning-theory approach. The process of "doing science" includes raising questions, planning and implementing experiments, and communicating new understandings. These tasks that can be authentically mirrored in "teaching science" as students identify an area of inquiry, plan and implement a hands-on activity, and communicate their learning via assessment methods. (Morrow, 2000), practices emphasized in the Framework for the NGSS.

Theoretical Framework

Science teachers, particularly at the elementary level, face formidable challenges in helping students achieve learning goals outlined in science education standards (e.g., Davis, Petish, & Smithey, 2006). Accordingly, the framework undergirding this study draws upon theory regarding teacher knowledge and the role of curriculum materials in effective science education.

A Professional Knowledge Base for Science Teaching

Prominent educators and researchers have proposed the existence of a professional knowledge base for teaching akin to the specialized knowledge bases for medicine and law (Shulman, 1986, 1987; Grossman, 1990; Hiebert, Gallimore, & Stigler, 2002; Hill, Rowan, & Ball, 2005). Efforts to articulate the components of such a knowledge base have been underway for nearly two decades. Some constituent knowledge forms, such as disciplinary content knowledge, are fairly well understood and accepted as necessary, but not sufficient for effective teaching (e.g., Heller, Daehler, Wong, Shinohara, & Miratrix, 2012). Similarly, knowledge of pedagogy and a vision of effective teaching are thought to be important components of a professional knowledge base for teaching (Shulman, 1987; Hammerness, 2003).

Synergistic relationships among components in the knowledge base for teaching have spawned discussion about another form of knowledge for teaching: pedagogical content knowledge. First proposed by Shulman (1986), pedagogical content knowledge, or PCK, is described as an amalgam of pedagogical knowledge (general teaching knowledge) and content knowledge (knowledge of a specific discipline). To this description of PCK, Grossman added knowledge of the context within which instruction happens, and knowledge of the goals and purposes for teaching specific content (Grossman, 1990). Building on Shulman and Grossman's work, Magnusson, Krajcik, and Borko (1999) developed a model of PCK for science teaching. Their model describes how teacher orientations to science teaching shape discrete forms of PCK for science teaching, including knowledge of science curriculum, knowledge of instructional strategies, and knowledge of students' understandings of science topics.

After years of research, there is an emerging consensus that PCK is important for science teachers, although the precise meaning of the construct is debated and a consensus understanding of just what constitutes PCK is lacking (Abell, 2008). At a recent weeklong international conference on science PCK, funded by NSF (PCK Summit; DRL-1206499), a group of researchers agreed that the problem was due largely to a debate over the idiosyncrasy of PCK. The Summit participants achieved a breakthrough of sorts by (1) agreeing that PCK is indeed personal; i.e., PCK resides in and is unique to a teacher, and (2) conceptualizing a new construct for the collective professional knowledge that resides outside the teacher, apart from his/her beliefs/orientations and context. That construct, "topic-specific professional knowledge"[1] (TSPK), is similar to the amalgam of content knowledge and other knowledge bases described by Shulman as PCK. However, TSPK represents professional knowledge that teachers can act on to develop personal PCK.

To teach science effectively, teachers need to draw on several forms of knowledge (e.g., Wallace & Louden, 1992). In addition to disciplinary content knowledge and general pedagogical knowledge, important aspects of TSPK for science teaching include knowledge of:

- how to capture students' interest in science by situating instruction in contexts and scenarios that are familiar and engaging for students;
- conceptions students likely have about the targeted ideas prior to instruction, as well as the experience-derived rationales for those conceptions;
- experiences and instructional strategies that will prompt students to reconsider their thinking *and* provide evidence for the consensus scientific idea;
- which elements of scientific learning opportunities are most salient in relation to the targeted idea, and how to help students attend to those salient aspects during instruction;
- how to support students in engaging in authentic scientific practices, such as making sense of data and forming evidence-based claims;
- how to help students connect specific phenomena/outcomes and ideas in science to arrive at more general understandings, or "big ideas"; and
- how to assess student understanding of the targeted ideas.

However, mastering these bodies of knowledge poses quite a challenge, especially at the elementary level where teachers are typically generalists, teaching reading/language arts,

[1] This term was suggested by Julie Gess-Newsome, PI of the PCK Summit project.

mathematics, and social studies in addition to science. Many elementary teachers do not have strong backgrounds in science, and may lack confidence in teaching science (Appleton, 2006; Banilower, et al., 2013). In addition, elementary teachers are often responsible for teaching a wide variety of science topics that span the earth, life, and physical sciences. To compound the problem, it is not uncommon for teachers to change grade levels, and thus be responsible for teaching different topics from year to year. Expecting elementary teachers to sift through research for TSPK and/or develop PCK for every science topic they may teach seems unrealistic. We posit that science curriculum materials can be engineered to alleviate some of this demand on teachers. In the following section, we discuss ways in which science instructional materials might incorporate some of the knowledge required for effective science instruction.

The Role of Instructional Materials in Science Teaching

Not surprisingly, elementary teachers often rely heavily on curriculum materials (Grossman & Thompson, 2004; Mulholland & Wallace, 2005). For a variety of reasons, most currently available curriculum materials in science do not foster effective science teaching. Many existing science curriculum materials contain content inaccuracies, do not adequately address state or national science education standards (Kesidou & Roseman, 2002; Stern & Roseman, 2004), and reinforce pedagogies that are not aligned with principles of effective science instruction. Additionally, many science curriculum materials do not incorporate TSPK derived from research and practice. For example, few extant science curriculum materials provide the teacher with descriptions of common student misconceptions for specific topics, and do not include supports for where and how student misconceptions may be or are addressed in the materials' instructional sequence.

We believe that science curriculum materials can be developed such that they are accurate, aligned with science education standards and principles of effective science instruction, infused with TSPK, and contain teacher-specific supports to guide successful enactment. Force and motion is a topic that is particularly amenable to the creation of high-quality, TSPK-embedded curriculum materials, as there is a considerable body of research on teaching and learning this topic, at a variety of grade levels (e.g., Clement, 1982; Hestenes, Wells, & Swackhamer, 1992; McDermott, 1997; Erilymaz, 2002). For example, it has been shown that students typically struggle with the idea that “An object in motion will remain in motion unless acted upon by an outside force” (Newton’s first law) because it runs counter to what they experience in their everyday lives. Consequently, misconceptions around this concept are highly resistant to change (Champagne, Klopfer, & Anderson, 1980; Champagne, Klopfer, & Gunstone, 1982). However, instructional strategies that have successfully supported students in changing their understandings of relationships between force and motion have been documented (e.g., Brown & Clement, 1989; Brown, 1992).

Utilizing research on teaching and learning of specific topics, and through the creation of educative supports, curriculum designers can embed TPSK in curriculum materials, including descriptions of common student misconceptions, research-based instructional strategies, and background knowledge for teachers to deepen their own understandings of the science content and how the instructional strategies can help students learn the targeted science content. Although still in its infancy, there is an emerging body of research around the roles and effects of educative curriculum materials in science education (Davis & Krajcik, 2005; Schneider & Krajcik, 2002; Beyer et al., 2009). This study adds to the growing body of knowledge about the effects of instructional materials designed to assist elementary teachers in teaching science topics in which they do not have PCK, or may not even have strong content knowledge.

Description of the Intervention

Teachers in the treatment group for this study were provided with a set of learning-theory aligned instructional materials for use in their own teaching of force and motion, and an implementation guide to support them in using these instructional materials. In addition, the treatment teachers attend a week of professional development during the summer of 2011.[2] These three parts of the intervention are described below.

Curriculum Materials

The force and motion curriculum materials were developed and structured according to research on how people learn, and took advantage of the relatively rich body of research on teaching and learning of this topic. Each lesson has a key question aligned with the targeted idea(s) and includes activities that provide evidence that allow students to answer this question. Each lesson also provides opportunities for students to surface their prior knowledge of the targeted idea, make evidence-supported claims, and make sense of the phenomena. Figure 1 provides an example of this structure:

[2] The Force and Motion curriculum materials and Professional Development were developed in collaboration with Dr. Steve Robinson, Chair of the Physics Department at Tennessee Tech University.

Unit 2 Cycle 1
Exploration #2: Forces without contact?

Targeted Idea: Some forces between objects act when the objects are in direct contact; others act when objects are not touching.

Elicitation:
Imagine there were some metal paper clips lying on the table in front of you. Do you think there is any way you could make them start to move without touching them? If so, how do you think you could do it?

Activities:
(1) Place a paperclip on one side of the table and slowly slide a magnet toward it.

(2) Rub a balloon up and down several times on your shirt. Now quickly bring the rubbed side of the balloon close to, but not touching someone else's hair.

(3) Rub a balloon up and down several times on your shirt. Now quickly bring the rubbed side of the balloon close to but not touching, some small pieces of shredded paper.

Using Evidence:

(1) Did the magnets apply a force to the paperclip before they touched each other? How can you tell?

(2) Does the balloon apply a force to the hair? How can you tell?

(3) Did the balloon apply a force to the paper before they touched each other? How do you know?

Making Sense:

(1) Can some objects apply forces to other objects without touching them? If so, give some examples.

Figure 1: Sample Lesson Structure in Force and Motion Curriculum Materials

The unit was intended to encompass approximately nine weeks of instruction (the amount of time designated in the state standards that should be devoted to the topic). In order to facilitate teacher adoption of the materials, the activities were designed to be easy and reliable to implement, and use low-cost and readily accessible materials.

Implementation Guide

We also developed an "educative" implementation guide for the curriculum materials to provide on-going support for teachers. This guide includes a summary of the learning-theory-based instructional model on which the materials are based, and specific implementation support for each lesson. For example, the introduction to each lesson lists the ideas targeted, naïve conceptions/misconceptions about those ideas that the research base indicates students are likely to have, and suggestions for focusing students on the relevant aspects of the activity (i.e., those that provide evidence for the consensus scientific idea). Figure 2 provides an example of the background information provided to teachers for each lesson.

Unit 1 Cycle 2
Beginnings: Is it moving?

Lesson Target Ideas:

- An object is in motion when its position is changing.
- When describing the motion of an object, both how fast it is moving (its speed) and its direction of motion are important pieces of information.
- The motion of an object can be represented using a number of different types of diagrams.

Common Misconceptions:

"Motion" means either moving or not moving. Students do not consider different categories of motion: at rest, constant speed, increasing speed, decreasing speed, changing direction, etc. Instead, they think of motion as simply either moving or not moving.

What to Focus On:

This cycle focuses on both motion (change in position) and changes in motion (change in speed and/or direction). These are not the same thing, but it is up to students to come to this realization, with the teacher's guidance. It is best not to tell them about the difference or define terms at this point. Instead, the teacher should give a general introduction such as: in the previous cycle you focused on objects that were not moving, so all you could give were their positions. However, now you will focus on moving objects and how to describe their motion.

In this activity, students draw diagrams to illustrate the motion of a car as it increases speed, travels at constant speed, and slows to a stop. Students should observe that there are various ways to show the speed and direction of a moving object and consider the advantages and disadvantages of their representations.

Prior to, and during, the part of the lesson where students draw motion diagrams of the car, the teacher should make sure that students are focusing on showing the different types of motion the car has at different times (increasing speed, constant speed, decreasing speed) and the direction in which the car moves. It is likely some students will be more focused on drawing a "cool" looking car or scenery than on the different stages of motion. In this case, the teacher should ask the students how their diagram shows each stage of motion. Some students may want to add new stages of motion to the scenario. If the teacher allows students to modify the scenario, it will be important to make sure the students' diagrams are consistent with the modified scenario.

Figure 2: Sample Teacher Supports in Force and Motion Implementation Guide

In addition, the implementation guide includes "Teacher Tips" that are embedded in the lesson and offer guidance throughout the various steps of each activity (see Figure 3).

Making Sense Question #1:

What important pieces of information are needed when describing the motion of an object?

Teacher Tip:

Elicit ideas from the class. The obvious candidates are speed and direction, but students may also think of position. If they do, then elicit the idea that it is the CHANGE in position that conveys the idea of motion, not just a single position on its own. To illustrate this you could describe the position of an object they cannot see and ask if they can tell from your description whether it is moving or not.

Figure 3: Teacher Tip in Force and Motion Implementation Guide

Professional Development

Although the implementation guide provides a great deal of support to teachers using the force and motion curriculum materials, there are several reasons why we felt it was also necessary to offer professional development. First, elementary teachers tend to feel less well prepared in the physical sciences than the other sciences. Second, because teaching science with a learning theory-based approach is not the norm, we thought it was important to introduce teachers to this approach to help develop a common vision of effective science instruction, and so they would understand the rationale for the design of the materials, both within and across lessons. Finally, because teachers were being asked to adopt a new set of curriculum materials, we thought it important to familiarize them with the structure of the materials so that they could navigate through them successfully and confidently.

Consequently, the Force and Motion Professional Development (PD) was designed with these priorities in mind. The PD provided opportunities for teachers to deepen their understanding of the targeted content using a learning-theory-based approach. This approach included eliciting teachers' initial thinking about the targeted ideas, engaging them with phenomena that provide evidence for the ideas, and providing explicit opportunities for sense making. The PD also emphasized the connections among the content ideas, in particular how the smaller ideas lead to the "big ideas."

The PD was also structured to engage teachers with the content in a way that they could easily take back and apply to the classroom. In addition to experiencing the lessons as learners, which familiarized them with how the activities are supposed to work, the PD included explicit discussions of the activities from the teacher perspective, and opportunities for teachers to consider how their own students might struggle with the content.

Finally, the PD specifically aimed to develop teacher understanding of why the PD and classroom materials were developed the way they were—that learning theory implies that learners need to be aware of their initial ideas, engage with phenomena that provide evidence for scientific ideas, draw and critique conclusions from this evidence, consider how their thinking changed, and apply their new understanding to other contexts. To develop teacher understanding of this instructional vision, the PD included periodic opportunities for teachers to step back from the science investigations and reflect on their own experience learning the content, as well as to explicitly discuss the pedagogical approaches utilized. Teachers were also provided with opportunities to analyze other teachers' classroom practice—through written vignettes and video—using a learning-theory lens.

Research Design and Methodology

Research Questions

Despite the research base on science learning, few currently available curriculum materials embody learning theory-based approaches to science education. Additionally, few currently available science curriculum materials incorporate a variety of teacher-targeted supports for content knowledge and content-specific pedagogy (Beyer, Delgado, Davis, &

Krajcik, 2009). As the NGSS are adopted throughout the U.S., and the demands on teachers and students change, high-quality, NGSS-aligned curriculum materials will become increasingly important tools for science education improvement at a large scale. In this proof-of-concept study, we examined the effectiveness of an elementary-level physical science curriculum unit that (1) is aligned with Framework for the NGSS physical science learning goals in force and motion, (2) has an underlying structure grounded in learning theory, and (3) contains supports to enhance teachers' enactment of the curriculum (TSPK). Specifically, this study used a quasi-experimental, two-group design to investigate the following research questions:

1. What is the impact of the unit on students' conceptual understanding of important ideas in force and motion, overall and for student subgroups (e.g., race/ethnicity, gender)?
2. To what extent does teacher content knowledge mediate the development of students' conceptual understanding?
3. To what extent does implementation fidelity of the unit affect the development of students' conceptual understanding?

Participants

Participants in this study came from three school districts in one Southern state and were purposefully assigned into treatment and comparison groups. The treatment group was composed of 25 5th grade teachers from two geographically adjacent school districts. The close proximity of the districts to the research team made it feasible to conduct extensive classroom observations, allowing us to address the third research question regarding fidelity of implementation on students' conceptual understanding. The comparison group of 39 teachers was composed of teachers from a third school district in the same state. All three districts encompass urban, suburban, and rural areas, and serve diverse student bodies.

Data Collection Activities

Teachers in both the comparison and treatment groups participated in a variety of data collection activities, as summarized in Table 1.

Table 1
Data Collection Activities for Treatment and Comparison Groups

	Pre-Unit	During Unit	Post-Unit
Teachers			
Treatment Group	*TCA, TQ1*	*CO*	*TQ2*
Comparison Group	*TCA, TQ1*		*TQ2*
Students			
Treatment Group	*SCA*	*CO*	*SCA*
Comparison Group	*SCA*		*SCA*

Student Content Assessment (SCA). Teachers in both the comparison and treatment groups administered a 25-item content assessment to their students before and after their unit on force and motion. The assessment items targeted conceptual understanding and used common misconceptions identified in the literature as distractors. The student assessment has an IRT reliability of 0.81 and covered the following ideas:

- An object's position can be described by locating the object relative to other objects or a background.
- The description of an object's motion from one observer's view may be different from that reported from a different observer's view.
- An object is in motion when its position is changing.
- The speed of an object is defined by how far it travels divided by the amount of time it took to travel that far.
- A change in motion is a change in its speed, or its direction, or both
- The motion of objects can be changed by pushing or pulling.

- The size of the change is related to the size of the force (push or pull) and the weight (mass) of the object on which the force is exerted.
- When an object does not move in response to a push or a pull, it is because another push or pull is being applied by the environment.
- A force is a push or pull exerted on one object by another object when they interact with one another.
- Earth pulls down on all objects with a force called gravity.
- With a few exceptions (e.g., helium filled balloons), objects fall to the ground no matter where the object is on Earth.

Teacher Content Assessment (TCA). All participating teachers completed a 30-item multiple-choice assessment prior to teaching their force and motion unit. As with the student assessment, the teacher assessment targeted conceptual understanding and utilized common misconceptions as distractors. In addition, the teacher items were all set in the context of teaching (e.g., asking teachers to analyze hypothetical student statements). The teacher assessment has an IRT reliability of 0.86 and encompasses the ideas on the student content assessment as well as several teacher-only ideas. These teacher-only ideas cover content that is important for teachers to know in order to teach the student ideas effectively:

- Dividing the distance traveled by the time taken gives the average speed of an object, as opposed to the speed at a particular instant.
- An object's motion can be described completely by its speed and the direction in which it is moving.
- An object's position can be measured and graphed as a function of time.
- An object's speed can be measured and graphed as a function of time.

- An object's mass is an inherent property, distinct from (but proportional to) its weight. The mass of an object is a measure of the amount of material comprising it.
- The term weight refers to the strength of the gravitational force exerted by the Earth on an object.
- Supporting objects, such as hands, tables, and shelves, exert upward forces on objects on top of them. These supporting forces exactly balance the downward pull of gravity and so these objects do not fall.
- Some forces between objects act when the objects are in direct contact or when they are not touching.
- Forces have magnitude and direction.
- Forces can be added. The net force on an object is the sum of all the forces acting on the object.
- A non-zero net force on an object changes the object's motion; that is, the object's speed and/or direction of motion changes.
- A net force of zero on an object does not change the object's motion.
- The force of friction acts to oppose the relative motion of two objects in contact.

Teacher Questionnaires (TQ1 and TQ2). All teachers completed two questionnaires, one before their force and motion unit and a second at the conclusion of the unit. The pre-unit questionnaire captured teachers' views about factors that affect their science instruction, their perceptions of preparedness to teach force and motion, and their beliefs about effective science instruction. The post-unit questionnaire focused on the teacher's instruction during their force and motion unit as well as students' attitudes toward school and science. For the treatment group, the post-unit questionnaire also asked about the extent to which they used the instructional materials that were provided.

Classroom Observations (CO). Members of the research team were able to observe the majority of the force and motion instruction of the treatment group, conducting over 500 classroom observations across the participating teachers. The information gathered during each observation was then analyzed using the AIM Classroom Observation Protocol (COP), a learning-theory aligned observation tool developed to gather information about student opportunity to learn targeted science ideas.

Study Design

To answer the research questions, treatment and comparison groups were compared through an analysis of student test scores, controlling for student and teacher characteristics. The analysis also tested whether teacher content knowledge mediated student learning. Finally, implementation factors were examined within the group of treatment teachers to see how fidelity to the pedagogical approach related to student learning.

Variables

The collected data were used to create a number of variables for the analyses. From the SCA and TCA, student achievement and teacher content knowledge variables were calculated using the total percent of correct responses. From the post-unit questionnaire, the total number of minutes of instruction devoted to force and motion was calculated by multiplying teacher responses to questions about the average number of minutes in a typical science lesson and the total number of lessons on the eight core force and motion concepts. The variable “extent to which the intervention unit was implemented” was calculated for treatment teachers who denoted whether they used each activity exactly as written, with modification, or not at all. In addition, classroom observations were used to classify teachers as having implemented the unit with high, medium, or low fidelity to the pedagogical approach.

Analysis and Results

Students in the treatment and comparison groups were quite similar demographically, with the exception being a 15 percent difference in the number of students self-identifying as American Indian or Alaskan Native, Black, Hispanic or Latino, or Native Hawaiian or Other Pacific Islander. Teachers in the treatment condition were somewhat more likely to be novice teachers or very experienced teachers (16 or more years) compared to teachers in the comparison group. Treatment teachers also tended to score higher on the content assessment (though their pre-PD scores were very similar to the comparison teachers' scores). On average, teachers in the treatment condition spent more time (approximately 2.7 hours) than teachers in the comparison group teaching force and motion. Descriptive statistics are presented in Tables 2–4.

Table 2
Descriptive Statistics – Student Data

	Percent of Students	
	Treatment Condition (N = 400)	**Comparison Condition (N = 781)**
Female	53	52
English as a Second Language Status	7	10
Historically Underrepresented in STEM[3]	38	53

[3] Includes students identifying themselves as American Indian or Alaskan Native, Black, Hispanic or Latino, or Native Hawaiian or Other Pacific Islander.

Table 3
Descriptive Statistics – Teacher Data

	Percent of Teachers	
	Treatment Condition (N = 25)	**Comparison Condition (N = 39)**
Teaching Experience		
0–5 Years	40	28
6–10 Years	8	23
11–15 Years	20	28
16+ Years	32	21
Fidelity to Pedagogical Approach		
Low	32	--
Medium	44	--
High	24	--

Table 4
Descriptive Statistics – Teacher Data

	Treatment Condition (N = 25)		**Comparison Condition (N = 39)**	
	Mean	**SD**	**Mean**	**SD**
Teacher Content Knowledge Test Score	78.27	10.05	57.07	13.35
Minutes Spent on Force and Motion Concepts	798.18	441.82	634.72	360.63
Extent of Use Composite Score	48.11	25.65	--	--

Data for this study were analyzed using a three-level regression model where assessment scores were nested within students and students were nested within teachers. (Teachers were seldom clustered within the same school, therefore a school level nesting structure was deemed unnecessary.) To account for the nested structure of the data through apportioning the variance across the nested levels the models were run using HLM version 7 software (Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2011). Student test scores served as the outcome variable in all models. As the models were built and each set of predictor variables added, random effects at the student and teacher level were tested and included when they improved model fit. The rest of this section is organized by research question.

Research Question 1: What is the impact of the unit on student achievement, overall and for student subgroups (e.g., race/ethnicity, gender)?

In the three-level model used to answer this question, the first level represents time points of the student test administration designated by a time point indicator (pre vs. post). The second level represents students and includes student demographic variables—dummy-coded variables for gender (female vs. not female), race/ethnicity historically underrepresented vs. not), and whether English is a second language for the student (ESL vs. non-ESL). The third level represents teachers, and includes teacher experience (categories: 0–5 years, 6–10 years, 11–15 years, 16 years or more, with the 0–5 category as the reference group) and a variable indicating whether the teacher was in the treatment or comparison group). All predictor variables, except the student post-test the treatment group indicators, were grand-mean centered. Figure 4 shows the final regression equations.

Level 1

$\text{Score}_{ijk} = \pi_{0jk} + \pi_{1jk}\text{Post}_{ijk} + e_{ijk}$

Level 2

$\pi_{0jk} = \beta_{00k} + \beta_{01j}\text{Female}_{jk} + \beta_{02j}\text{ESL}_{jk} + \beta_{02j}\text{Historically Underrepresented}_{jk} + r_{0jk}$
$\pi_{1jk} = \beta_{10k} + \beta_{10j}\text{Female}_{jk} + \beta_{12j}\text{ESL}_{jk} + \beta_{12j}\text{Historically Underrepresented}_{jk} + r_{1jk}$

Level 3

$\beta_{00k} = \gamma_{000} + \gamma_{001}\text{Treatment}_k + \gamma_{002}\text{6-10 Years of Experience}_k + \gamma_{003}\text{11-15 Years of Experience}_k + \gamma_{004}\text{ 16 or more Years of Experience}_k + u_{00k}$
$\beta_{01k} = \gamma_{010}$
$\beta_{02k} = \gamma_{020}$
$\beta_{03k} = \gamma_{030}$
$\beta_{10k} = \gamma_{100} + \gamma_{101}\text{Treatment}_k + \gamma_{102}\text{6-10 Years of Experience}_k + \gamma_{103}\text{11-15 Years of Experience}_k + \gamma_{104}\text{ 16 or more Years of Experience}_k + u_{10k}$
$\beta_{11k} = \gamma_{010}$
$\beta_{12k} = \gamma_{020}$
$\beta_{13k} = \gamma_{030}$

Figure 4: Regression equations used for research question one.

The analysis found that students of treatment teachers had significantly greater gains from pre- to post-test than students of comparison group teachers, controlling for student and teacher demographics (see Table 5). Treatment gains were, on average, 4.24 points higher than comparison group gains, an effect size[4] of 0.21 standard deviations. There were no significant differences in gains for the various subgroups of student subgroups.

Table 5
Impact of Unit on Student Achievement: Model 1 Results

	Coefficient	**Standard Error**	**Effect Size (standard deviations)**
Pre-test score	50.78	1.23	
Student-Level Predictors			
Female	-2.66*	0.90	0.13
Historically Underrepresented	-10.42*	1.06	0.52
English is Second Language	-1.79	1.72	
Teacher-Level Predictors			
Treatment	-7.14*	2.04	0.36
Teacher Experience (Referent Group: 1–5 Years)			
6–10 Years	4.60	2.94	
11–15 Years	4.61	2.57	
16 or more Years	5.02	2.55	
Gain from Pre to Post	10.21*	0.83	0.51
Student-Level Predictors			
Female	0.02	0.82	
Historically Underrepresented	-1.40	0.93	
English is Second Language	0.04	1.55	
Teacher-Level Predictors			
Treatment Teacher	4.24*	1.38	0.21
Teacher Experience (Referent Group: 1–5 Years)			
6–10 Years	-2.01	1.99	
11–15 Years	-0.32	1.73	
16 or more Years	-1.91	1.72	

* $p < 0.05$
Note: All variables are grand-mean centered except for the "gain from pre to post" and "treatment teacher" indicators.

An alternative model was run that also included the total number of minutes of instruction on force and motion concepts. Time spent on force and motion concepts was not a significant predictor of student gains, and other model variables, including the treatment group

[4] Effect size is calculated as the regression coefficient divided by the standard deviation of student test scores.

indicator, yielded similar estimates. For ease of presentation only the initial model results are reported.

Research Question 2: To what extent does teacher content knowledge mediate student learning?

Using an approach developed by Barron and Kenny (1986) and adapted for tests of multilevel mediation using hierarchical linear models (Zhang, Zyphur, & Preacher, 2009), the results from model shown in Table 5 were compared to the results of a model that included teacher content knowledge assessment scores (denoted TCK, grand-mean centered) at the teacher level (the models were identical in all other ways). The estimate of the mediation effect is calculated by subtracting the estimate of the treatment effect in the model that contains the mediation variable from the estimate of the treatment effect in the original model (Freedman and Schatzkin, 1992). A test of the significance of the mediator estimate was not significant; t (2396) = 0.31, p > 0.05 (see Table 6), indicating that there is no evidence that teacher content knowledge plays a role in the effect of the treatment on student achievement.

Table 6
Test of the Mediating Effect of Teacher Content Knowledge

Estimate of Treatment Effect		**Estimate of Mediator (TCK) Effect**	**Test of Significance**
Model 1 (C)	*Model 1 + TCK (C')*	*C-C'*	$t_{n-2} = \frac{c - c'}{\sqrt{\sigma_c^2 + \sigma_{c'}^2 - 2\sigma_c\sigma_{c'}\sqrt{1-\rho_{xm}^2}}}$
4.24	3.85	0.38	t (2396) = 0.31, p > 0.05

Research Question 3: To what extent does implementation fidelity affect student learning?

The analysis of the effect of implementation fidelity on student achievement was based on the 25 treatment teachers. In this model, the first and second level equations remain the same as the model shown in Figure 4, and additional variables that capture aspects of implementation fidelity, based on observation data, were added to level three (teachers). Two variables were added to indicate the level of fidelity to the pedagogical approach (low or high fidelity, with individuals in the medium category serving as the reference group). Another variable was entered to indicate the extent to which teachers used the provided curriculum materials. All predictor variables, except for the student post-test indicator, were grand-mean centered.

The results show that students of teachers classified as high fidelity implementers had greater achievement gains than students of medium fidelity teachers (see Table 7). The approximately 8-point greater gain from pre to post translates into an effect size of 0.40 standard deviations. The extent of use variable was not a significant predictor of student gains.

Table 7
Examination of Implementation: Model Results

	Coefficient	**Standard Error**	**Effect Size (standard deviations)**
Pre-test score	44.19	1.07	
Student-Level Predictors			
Female	-1.33	1.60	
Historically Underrepresented	-10.60*	1.76	0.53
English is Second Language	3.84	3.35	
Teacher-Level Predictors			
Extent of Use	-0.17*	0.06	0.01
Fidelity to the Pedagogical Approach (Referent Group: Medium)			
Low	1.88	2.62	
High	6.27	3.35	
Teacher Experience (Referent Group: 1–5 Years)			
6–10 Years	5.91	4.15	
11–15 Years	12.02*	3.01	0.60
16 or more Years	8.96*	2.96	0.45
Gain from Pre to Post	14.54*	1.18	0.73
Student-Level Predictors			
Female	-1.21	1.45	
Historically Underrepresented	1.31	1.62	
English is Second Language	-2.34	3.05	
Teacher-Level Predictors			
Extent of Use	-0.04	0.06	
Fidelity to the Pedagogical Approach (Referent Group: Medium)			
Low	2.19	2.87	
High	8.03*	3.68	0.40
Teacher Experience (Referent Group: 1–5 Years)			
6–10 Years	-3.85	4.62	
11–15 Years	1.43	3.23	
16 or more Years	-0.63	3.25	

* $p < 0.05$
Note: All variables are grand-mean centered except for the posttest indicator.

Discussion

The overarching goal of this study was to examine whether the use of learning-theory aligned instructional materials could improve elementary student conceptual understanding of ideas about force and motion. Although this study was conducted on a relatively small scale, and in a limited context, the results provide some evidence of the efficacy of these materials for increasing student knowledge, as students of teachers who used the instructional materials had greater learning gains than students of teachers who did not. Although the teachers in this study did receive PD in addition to using the materials, we think it likely that teachers who understand and have a vision of learning theory-based instruction would need substantially less PD than provided as part of this study. In addition, we expect that once teachers are familiar with instructional materials designed this way would need substantially less PD to implement additional units of this type.

This study also found that teacher disciplinary content knowledge, as measured by an assessment aligned with the content of the instructional unit, was not a significant mediator of gains in student understanding. This finding may suggest that high-quality, learning-theory aligned instructional materials with educative supports may help “level the playing field,” by providing purposeful opportunities for teachers to deepen their understanding of the content while teaching the unit. Lastly, fidelity to the pedagogical principles embodied in the materials was a strong predictor of student learning gains.

The NGSS provide both opportunities and challenges for improving K–12 science education in the U.S. Successful implementation of the NGSS will require system-wide efforts, including changes to teacher pre-service and in-service education, assessments, and instructional materials. These challenges are magnified at the K–5 level as most elementary teachers are expected to be generalists and teach multiple subjects to students. Although professional development can help elementary teachers deepen their understanding of science and how to teach it, it would require an enormous investment of time and money to provide sufficient professional development for all elementary teachers to develop TSPK and PCK in each science topic they teach. This study provides evidence for using a new model for instructional material to develop teachers’ knowledge and skills at teaching science. Embedding TSPK within instructional materials, and training teachers to use this type of instructional materials, is a scalable and potentially cost-effective approach to improving elementary science education.

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