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LEARNING

Improving Middle School Science Learning Using Diagrammatic Reasoning

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ABSTRACT: We explored whether existing curricula can be adapted to increase students' skills at comprehending and learning from diagrams using an intervention delivered by regular middle-school teachers in intact classrooms. Ninety-two teachers in three states implemented our modified materials over six curricular units from two publishers: *Holt* (a reading-focused curriculum) and *Full Option Science System* (*FOSS*) (an inquiry-focused curriculum). Results were compared between two interventions—one based on selected principles of cognitive science (cognitive-science-based) that included instruction in diagram comprehension and one providing professional development in science content only (content-only)—and a business-as-usual control. We analyze posttest items involving different degrees of reliance on diagrams to show how instruction in diagram comprehension can improve comprehension of diagrams during reasoning. At the classroom level, there were significant advantages of the cognitive-science-based intervention over both content-only and business-as-usual with large effect sizes in all *FOSS* units ($d = 0.41$–0.52), but only one *Holt* unit ($d = 0.11$). Analyses by type of diagram suggested these effects were largest for transfer to diagrams from an uninstructed domain. Further analyses of high-stakes state test

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scores available for the participants implementing the *Holt* units showed improved use of diagrams ($d = 0.45$–0.66). Results suggest that making sense of visualizations (diagrams) is not effortless and self-evident, but that students who receive supports for comprehending can improve their comprehension, and the learning can transfer to new domains. *Sci Ed* 1–30, 2016

INTRODUCTION

Today's students need to be prepared for participation in an increasingly scientific and technological society, in roles ranging from acting as informed citizens (e.g., on laws relating to future medical technologies) to becoming future scientists and innovators. Recent initiatives such as the Next Generation Science Standards (NGSS Lead States, 2013) and the science literacy strand of the Common Core State Standards (Common Core, 2011) have changed teaching standards to respond to the need to improve science education in the United States. These standards put new emphasis on higher order thinking. In this paper, we explore whether existing curricula can be adapted using selected principles from cognitive science to improve reasoning about complex scientific situations.

Specifically, we focus on whether we can increase students' skills at comprehending and learning from scientific diagrams (an aspect of metarepresentational competence; diSessa, 2004) using an intervention that is delivered by current teachers in traditional classrooms, going beyond past successes with lab-based or researcher-delivered instruction. The intervention was implemented using summer professional development, coupled with providing supportive material and school year teacher discussion, in a randomized controlled trial with three arms: the intervention (cognitive-science-based intervention), an active control group in which teachers received professional development on science content (content-only group), and a business-as-usual control group.[1] Furthermore, similar interventions were implemented within two curricular frameworks, one a traditional text-based curriculum and the other a project-based curriculum designed to foster students' use of scientific methods.

Challenges of Diagram Comprehension

There is ample evidence that students have difficulty comprehending diagrams and translating among multiple representations, due to lack of knowledge about conventions of diagrams (e.g., Cromley et al., 2013), how to coordinate multiple scientific representations (e.g., Bergey, Cromley, Kirchgessner, & Newcombe, 2015; Cook, Carter, & Wiebe, 2008; Jian & Wu, 2015; Kragten, Admiraal, & Rijlaarsdam, 2015; Wu, Krajcik, & Soloway, 2001), and failure to construct their own diagrams (Schwamborn, Thillmann, Opfermann, & Leutner, 2011). Middle school science students are presented on a daily basis with visual representations such as diagrams, graphs, and photographs, yet students continue to struggle to make sense of these representations (Gilbert, Reiner, & Nakhleh, 2008). These difficulties have been documented through analyses of responses to standardized tests (Crisp & Sweiry, 2006), manipulations of diagram features in laboratory studies (Bodemer & Faust, 2006), think-aloud studies (Kragten, et al., 2015), eye tracking studies (Cook et al., 2008; Jian & Wu, 2015), and observations of students using and making diagrams in classrooms (e.g., Ero-Tolliver, Lucas, & Schauble, 2013). Furthermore, such challenges have been found

[1] As is typical for randomized controlled trials, we used a posttest-only design, with adjustments for students' prior academic achievement with these 24,725 students (e.g., see Harris et al., 2015). Such a design minimizes the data that would be expected to be missing due to absences at pretest or posttest.

specifically with biology diagrams at age ranges from elementary school (e.g., McTigue & Croix, 2010) to adult biologists and biology educators (Kindfield,1993/1994).

Conventions of diagrams are basic representational tools—such as arrows, color keys, and captions—developed since the Enlightenment to convey information about components and relations among components in visual representations. Some conventions (e.g., labels) simply name parts, whereas others may explain relations among parts (e.g., captions). Cutaways show interior parts in a two- or three-dimensional format, and color keys can be used to show boundaries of parts with specific functions (e.g., areas of the heart that carry oxygenated vs. deoxygenated blood) or to mark parts that are the same (e.g., a nucleotide base). Arrows can have several different functions, such as showing the flow or path of a substance or of energy; showing sequences over time (e.g., evolution of forelimbs); showing physical causes and effects; or showing increases or decreases (e.g., of pressure, temperature).

As such, conventions are central to multiple cognitive (e.g., Hegarty, 2005; Larkin & Simon, 1987; Mayer, 2005) and semiotic (e.g., Roth & McGinn, 1998) theories of diagram comprehension. All of these theories assume that to form an internal mental representation of what is depicted in a diagram, the reader must know what arrows in the diagram might mean, what symbols such as $+$ or Δ stand for, and the usefulness of reading labels of parts. Students weak in science perform especially poorly on test items that include diagrams, suggesting that these students lack basic understanding of these representations. Therefore, intervention at the most basic level should yield larger effects for low-skilled learners, compared to intervention at higher levels such as fostering inferences while reading diagrams (Butcher, 2006). Specifically, we reasoned that low-skilled learners in large city school systems, which tend to include more students underrepresented in the sciences (i.e., African American and Latino/Latina students), might especially benefit from such interventions. Given the lack of racial and ethnic diversity of the current science and engineering workforce, it is especially important to investigate interventions that support, or at least do not disadvantage, students underrepresented in the sciences.

The Design of a Cognitive-Science-Based Intervention

We systematically revised three units from each of two widely used science curricula in our cognitive-science-based intervention in a variety of ways (see http://www.cogscied.org for a complete description). We drew on four specific and relatively untested principles of cognitive science for which there was ample evidence from laboratory studies to suggest that they might be helpful to students in classrooms: (1) instruction in comprehending visualizations, (2) contrasting cases, (3) targeting misconceptions, and (4) spaced testing. The student *visualization exercises* (described below) and contrasting cases were implemented via brief 5–10 minute segments delivered by teachers each day in the context of their regular scope and sequence of instruction. Work addressing misconceptions was embedded within both of those types of exercises and teacher explanations. Spaced testing was implemented with daily warm-ups and weekly "pop quizzes" on material presented 2 days to 2 weeks previously. Each of these components represented a testable intervention, which could be combined with classroom topics taught in the regular scope and sequence and implemented by teachers in situ supported by ongoing professional development, and whose effects could be tested with end-of-intervention measures. In addition, the components are not completely unrelated to prior research in science education (e.g., specific physics misconceptions identified by Hunt & Minstrell, 1994; curricular coherence, Squires, 2009), but were designed based on specific, recent guidelines from cognitive science research such as optimal spacing for spaced testing.

For the purposes of this paper, we focus on the *visualization exercises* component of the intervention and visualization-specific posttest measures.[2] Our curricular revisions were aimed at teaching students how to interpret and use figures, graphs, and tables. Classroom-based interventions in diagram comprehension have rarely been tested experimentally, except for those using technology (Bergey et al., 2015; Cromley et al., 2013; Scheiter, Schubert, Gerjets, & Stalbovs, 2015; Schlag & Ploetzner, 2011; Schwamborn et al., 2011). Hence, we designed the diagram instruction within our cognitive-science-based intervention to convey the most basic information about diagrams, such as the meanings of numbering systems and color keys, and the importance of reading captions. This diagram instruction delivered in the cognitive-science-based condition was embedded within the same middle school science curricula as the other modifications, which focused on improving understanding and retention of core science content. The diagram instruction drew on the research base on instruction in comprehension of visuals, both in classes (e.g., Schlag & Ploetzner, 2011) and using technology (e.g., Schwamborn et al., 2011).

We specifically designed end-of-unit test items to investigate transfer to uninstructed diagrams, because there is relatively little research on whether visual representation comprehension skills can transfer to new stimuli from the same domain or between domains. Specifically, we see the need for students to learn how to approach all different types of diagrams across multiple domains, not just be able to answer questions about the specific diagrams they learned from. This is most consistent with De Corte's view of transfer as "the broad, productive, and supported use of acquired knowledge, skills, and motivations, as opposed to the direct and sequestered application of skills from one situation to another" (2003, p. 143). Expanding on this definition, our measures tapped what Schönborn and Bögeholz (2009) term "horizontal transfer" (within the same level of biological organization, across organisms) and "vertical transfer" (general principles, applied across different levels of biological organization).

Positive results for horizontal transfer of diagram instruction on researcher-developed tests are found in some lab-based research (Hegarty & Just, 1993; Hegarty & Sims, 1994; Hegarty, Kriz, & Cate, 2003; Kozhevnikov, Motes, & Hegarty, 2007; Ozcelik, Karakus, Kursun, & Cagiltay, 2009), whereas some studies find no transfer (Scheiter, Gerjets, & Catrambone, 2006; Schwamborn et al., 2011). In addition to testing both "horizontal" (same-domain) and "vertical (different domain) transfer in the present research, we also analyzed whether positive effects of the intervention could be observed on the items involving diagrams within tests that we did not develop–standardized science tests developed by and required for eighth-grade students in those states; these state tests also took place much later than the modified units.

Differential Effects on Students Underrepresented in Science

From a policy standpoint, it is critical that innovative interventions do not further disadvantage students from groups historically underrepresented in science (Under-Represented Minorities, hereafter URMs, i.e., African American and Latino/Latina students). Underrepresented minorities are more likely to attend underachieving schools in low-Socio-Economic Status (SES) neighborhoods; even after accounting for differences in personal characteristics, African American students show lower achievement when they are in high-minority schools (Bohrnstedt, Kitmitto, Ogut, Sherman, & Chan, 2015). Thus, we analyzed

[2] No results from other components of the larger study have been published.

our data using the 90% cutoff which Orfield (2009) defined as "highly segregated." It is unclear why the high-minority context is harmful, but a number of district-level (e.g., per capita funding from the neighborhood tax base), school-level (e.g., level of teacher experience), and classroom-level (e.g., teacher expectations, percent of fellow students whose parents have low levels of education) factors have been identified. Based on both policy demands—interventions should not disadvantage URMs—and known higher achievement challenges in high-URM schools, we investigated school-level percent URM as a moderator of the effects of our intervention.

Hypotheses

In Study 1, we report results for researcher-developed diagrammatic posttest items across both curricular modifications, examining whether benefits are found for items with differential dependency on diagram content as well as across different learners (URM) and learner contexts (class URM%). Our specific hypotheses for Study 1 are as follows:

1. Students in the cognitive-science-based intervention will outscore those in either the content-only or business-as-usual control groups on directly instructed diagrams. This represents a form of "horizontal" transfer in the Schönborn and Bögeholz (2009) framework.
2. Students in the cognitive-science-based intervention will outscore those in either the content-only or business-as-usual control groups on familiar-content, uninstructed diagrams. This also represents a form of "horizontal" transfer.
3. Students in the cognitive-science-based intervention will outscore those in either the content-only or business-as-usual control groups on unfamiliar-content, uninstructed diagrams. This represents a form of "vertical" transfer.
4. The proportion of URMs in a school may be associated with lower effectiveness of the intervention, even after controlling for student prior achievement, because of known challenges to achievement in high-minority schools.

In Study 2, we investigate whether these findings obtained with researcher-developed diagram questions are also found on measures less susceptible to confirmation bias–standardized state science tests.

STUDY 1

Method

Participants.

Holt Curriculum Participants. The participants included for data analysis were drawn from 88 schools in a large urban school district in the Eastern United States who participated in 2009–2011. There were 9,611 seventh- and eighth- grade students ($M = 12.7$ years, $SD = 0.5$) and 129 teachers. Forty of those teachers taught in 30 schools that were classified as academically low-performing schools. Students and teachers participated as part of their regular science classes across two consecutive cohorts (in the 2009–2010 and 2010–2011 school years) . Teachers were experienced in teaching science at the sixth- through eighth-grade level ($M = 7.1$ years, $SD = 5.9$). Most schools (66 of 94) had only one participating teacher ($M = 1.40$, $SD = 0.72$), and each teacher taught a mean of 2.5 sections of biological science ($SD = 1.25$). After centering previous state achievement scores on the test mean, average scores (combined math and reading) across classrooms ranged from

–291.01 to +272.43 ($M = 0.88$, $SD = 95.04$). Table 1 presents centered previous achievement scores, and demographic information about the teachers and students organized by subset (i.e., 7,240 *URM students,* 2,371 *non-URM,* 4,066 students in *higher-URM-proportion classrooms*,[3] and 5,545 students in *lower-URM-proportion classrooms*).

Full Option Science System (FOSS) Curriculum Participants. Participants were drawn from 96 schools in a large urban school district in the Eastern United States and a large urban/suburban district in the Southwestern United States who participated in 2009–2011. There were 15,114 sixth- and seventh-grade students ($M = 11.7$ years, $SD = 0.5$) and 165 teachers. Students and teachers participated as part of their regular science classes across two consecutive cohorts (2009–2010 and 2010–2011). The preponderance of schools (46 of 96) had only one participating teacher ($M = 1.80$, $SD = 1.00$). Table 1 shows students organized by subset (i.e., 8,511 *URM students,* 6,564 *non-URM,* 5,428 students in *higher-URM-proportion classrooms*, and 9,686 students in *lower-URM-proportion classrooms*).

Design.

Holt Curriculum. We used a randomized controlled trial design, with 97 schools initially randomly assigned to one of the three arms/conditions (see Table 2). There were 32 schools in the cognitive-science-based condition, 34 in the content-only condition, and 31 in the control condition. Within each school, all seventh-grade science teachers were assigned to the same condition for two consecutive years, provided that they remained employed as science teachers at that same school. This school-level random assignment was designed to minimize contamination across conditions. If teachers transferred to a school that had been assigned to a different condition, we terminated their participation in the study to reduce the risk of cross-contamination.

After the first year of the study, 91% (88) of the schools remained; after the second year, 80% (78) of the original schools remained. Schools in the cognitive-science-based condition were slightly more likely to be retained in Year 2 (84%; 27 schools) than were schools in the content condition (77%; 26 schools). Students in the control condition were more likely to have missing end-of-unit test scores in the first year (25% of students) than students in the content (14%) and cognitive-science-based (18%) conditions. In the second year, there was more student attrition from the content-only condition (18%) than from the control (15%) and cognitive-science-based (15%) conditions. Because schools had been randomly assigned to conditions well before students were enrolled in classes, all students can be considered joiners to the three conditions. The attrition rates and differences in attrition rates were within typical levels for Randomized Controlled Trials in education (Valentine, 2009).

FOSS Curriculum. Ninety-six schools were initially randomly assigned to one of the three arms/conditions (see Table 2). There were 34 schools in the cognitive-science-based condition, 30 in the content-only condition, and 32 in the control condition. Assignment was done as with the Holt schools. After the first year of the study, 93% (91) of the schools remained. Schools in the cognitive-science-based condition were about equally likely to be retained in Year 2 (91%; 31 schools) as were schools in the content-only condition (97%; 29 schools). As above, all students can be considered joiners to the three conditions.

Standard Curriculum. The standard curricula for the school districts were *Holt* or *FOSS. Holt Science and Technology* (Holt, Rinehart, & Winston, 2007) is widely used in

[3] Using Orfield's (2009) definition of highly segregated school settings as those with 90% or more URMs.

TABLE 1
Teacher and Student Participant demographics

Moderator or Measure	Description	URM Students	Non-URM Students	Students in Higher URM Proportion Classrooms	Students in Lower URM Proportion Classrooms
	Holt				
		$n = 7{,}240$	$n = 2{,}371$	$n = 4{,}066$	$n = 5{,}545$
Teacher					
CogSci1	Teacher is implementing intervention for the first time	25%	24%	22%	27%
CogSci2	Teacher is implementing intervention for the second time	8%	9%	5%	11%
Content1	Teacher has received content training for the first time	20%	19%	25%	17%
Content2	Teacher has received content training for the second time	12%	8%	13%	10%
Control1	Teacher is participating as a control for the first time	21%	24%	22%	22%
Percent URM	Percentage of teacher's students who are of traditionally underrepresented ethnicities	$M = 85\%$ $SD = 20\%$	$M = 47\%$ $SD = 23\%$	$M = 98\%$ $SD = 2\%$	$M = 58\%$ $SD = 24\%$
Student					
Female	Female student	49%	50%	49%	49%
Previous achievement	Student's grand-mean-centered state testing scores in reading and math from fifth and sixth grades	$M = -28.85$ $SD = 183.62$	$M = 93.68$ $SD = 197.53$	$M = -33.18$ $SD = 184.67$	$M = 26.44$ $SD = 197.47$
URM	Student is of a traditionally underrepresented ethnicity within STEM professions (i.e., not Asian or White)	100%	0%	97%	*58%*

(*Continued*)

TABLE 1
Continued

Moderator or Measure	Description	URM Students	Non-URM Students	Students in Higher URM Proportion Classrooms	Students in Lower URM Proportion Classrooms
	FOSS				
		$n = 8{,}511$	$n = 6{,}564$	$n = 5{,}428$	$n = 9{,}686$
Teacher					
CogSci1	Teacher is implementing intervention for the first time	10%	7%	13%	7%
CogSci2	Teacher is implementing intervention for the second time	25%	28%	24%	27%
Content1	Teacher has received content training for the first time	12%	9%	15%	8%
Content2	Teacher has received content training for the second time	17%	22%	12%	24%
Control1	Teacher is participating as a control for the first time	11%	13%	12%	11%
Percent URM	Percentage of teacher's students who are of traditionally underrepresented ethnicities	$M = 71\%$ $SD = 25\%$	$M = 38\%$ $SD = 21\%$	$M = 87\%$ $SD = 10\%$	$M = 38\%$ $SD = 17\%$
Student					
Female	Female student	50%	49%	50%	49%
Previous achievement	Student's grand-mean-centered state testing scores in reading and math from fourth and fifth grades	$M = -23.22$ $SD = 295.15$	$M = 29.81$ $SD = 334.98$	$M = -41.67$ $SD = 279.92$	$M = 23.35$ $SD = 329.39$
URM	Student is of a traditionally underrepresented ethnicity within STEM professions (i.e., not Asian or White)	100%	0%	87%	58%

All percentages were calculated out of the number of students in that subset of the data. For example, 49% of 7,240 Holt URM students are female. Percentages for conditions are based on the percentages of students who attended those schools/arms

TABLE 2
Number of Teachers per Intervention per Curriculum

	Curriculum					
	FOSS			Holt		
Characteristic	DOL	WW	EH	ITM	CELLS	IRE
Total number of teachers	167	175	134	171	189	155
Cognitive-science-based	67	71	48	59	63	53
Content-only	45	47	39	51	61	44
Control	55	57	47	61	65	58

Note: DOL = Diversity of Life, WW = Weather and Water, EH = Earth History, ITM = Introduction to Matter, CELLS = Cells, Heredity, and Classification, IRE = Inside the Restless Earth.

the United States. It is part of a short-course series self-described as combining the content teachers need with an accessible design, student friendly narrative, and vivid visuals. The *Holt* curriculum is more teacher focused and reading focused than the *FOSS* curriculum (described below). Although some active learning, hands-on, and inquiry activities are available, they are supplementary to the textbook, rather than at the heart of it. Participating schools taught one of three Holt short courses: *Cells, Heredity and Classification* (taught in seventh grade), *Introduction to Matter* (taught in eighth grade), or *Inside the Restless Earth* (taught in eighth grade).

The Holt curriculum contains more content than activities, which contrasts with the other curriculum, FOSS (developed by The Regents of the University of California). Participating schools taught one of three FOSS units: *Diversity of Life, Weather and Water*, or *Earth History*. The FOSS curriculum is focused on hands-on experiments and includes extensive materials provided to teachers in kits; by contrast, in Holt, learning happens primarily through reading. The Holt-modified units were taught at the beginning of seventh grade (approximately 4 months for Cells) and the beginning of eighth grade (approximately 3 months for Introduction to Matter and then another 3 months for Inside the Restless Earth). The FOSS-modified units were taught in seventh grade (Diversity of Life and Weather and Water) and eighth grade (Earth History) at varying times (each of approximately 3 months) during the year due to the need for school districts to rotate access to the science kit materials across schools. Both curricula were well aligned to the science standards set by the two states that were in effect at the time of the study.

Cognitive-Science-Based Condition. The cognitive-science-based intervention incorporated three major components (visualization exercises, case comparisons focused on highlighting key science concepts, and spaced testing in the form of daily warm-up questions and repeated/delayed questioning on quizzes and tests) that were interleaved into the same base unit (i.e., Holt Introduction to Matter, Cells or Inside the Restless Earth; FOSS Diversity of Life, Weather and Water, or Earth History). Although the intervention was also designed with applications of our fourth principle, *confronting misconceptions* (i.e., the necessity to confront and remedy inadequate or incorrect prior conceptions repeatedly to have students construct more accurate mental representations), that principle did not necessitate its own specific activities but instead informed the design of the other activities (e.g., it informed the selection of which concepts needed the most support). Our objective here is not to detail each supplementary activity at length but to give the reader a sense of each type of modification and the amount of time devoted to these supplementary activities.

The intervention was supplementary to the standard curriculum, not a replacement for it. Consistent with the literature (see Alfieri, Nokes-Malach, & Schunn, 2013 for a meta-analysis), case comparisons were designed as a more effective introduction to a new topic, whereas the visual demands of the chapters drove the visualization exercises, which were dispersed across days of the unit. All of the interventions were integrated into the entire unit, and its implementation took place during the same 3–4 month time span when the unit was ordinarily delivered.

Each modified unit was content analyzed using the Surveys of Enacted Curriculum framework constructed by Porter and colleagues (Porter, 2002). The Surveys of Enacted Curriculum include ratings for five types of cognitive demand from instructional materials: memorization, performing, communicating, analyzing, and applying, and each topic in the curriculum is categorized into one of these levels of demand, yielding percentages of each type of demand within each curriculum. Cognitive demand quantifies the requirements of the tasks that students are asked to undertake; proportions of performing and memorization were very similar across the units, except that *Cells* had a high proportion of memorization (63% of tasks required memorization), suggesting it was an easier unit. *Earth History* was rated much higher than the other curricula on analysis (21% of tasks required analysis), suggesting it was the hardest unit, with *Inside the Restless Earth* highest on communication (31% of tasks required communication) and also high on analysis (15% of tasks required analysis). We return to these differences in the Surveys of Enacted Curriculum demand ratings in the discussion.

Teacher Professional Development. Before implementing a modified unit, cognitive-science-based teachers attended 3 paid days of summer professional development per unit they were implementing. In the professional development, we explained the rationale for the revised activities (the cognitive principles involved) and how to implement those activities. Each teacher received a binder (CASEbook) that included a written introduction to the unit-specific intervention: its scope, contents, and goals, along with a CD of prepared PowerPoint presentations and any specialized materials needed to complete activities in the modified curriculum. The CASEbook also included the entire unit's planned activities (both standard and supplementary, including our chapter tests), and outlines of each day's activities (objectives, materials, schedule, etc.) which included explanations of what students should do during each task, the intended conclusions, and suggestions for how teachers could use the daily PowerPoints. For each unit, teachers also attended four after-school, small group follow-up sessions (one per month of the unit) to discuss challenges and successes.

The study was planned to be implemented for two cohorts of students, each cohort participating in sixth- and seventh-grade FOSS units (2 years, cross-sectionally) and seventh- and eighth-grade units (also 2 years, cross-sectionally) for Holt. Therefore, when new teachers began science teaching in a cognitive science school in the second year of implementation, they received makeup professional development during the summer and the school year similar to that provided in the first year. Teachers returning to the same condition for a second-year were provided with a brief overview of minor improvements to the intervention based on teacher feedback, and with additional after-school follow-up sessions similar in format to those in the first year.

Student Materials. Although most of the modifications were teacher materials, student materials for the intervention included case cards and worksheets. These provided necessary information about cases or prompted explanations of cases (through questions about their similarities, differences, etc.) when teachers presented the cases with PowerPoint slides.

Visualization exercises comprised slides that we asked teachers to display and/or involved directing student attention to images in their textbooks, whereas the teacher guided a discussion of the components of the image and their interpretations using suggested prompts. Visualization exercises were most often designed to be carried out as teacher-led, class discussions. The materials rarely asked for students to complete worksheets, but sometimes involved students taking notes in notebooks. As an example, the teacher was asked to display the three images of organisms (a mushroom photograph at real-life scale, yeast photographed though a microscope, and penicillium mold photographed though a microscope) and ask, "Which one of these is the largest? And, why do you think so?" or display the diagram and ask, "What does this arrow represent? What are the illustrators trying to tell us?" Then the teacher would provide explanations as necessary.

A warm-up question was designed to begin each day's activities, specifically connecting to previously learned content that was randomly selected from material covered 2 days to 2 weeks previously consistent with research on spaced testing (see Rawson & Dunlosky, 2011). Teachers were either asked to have students write out answers and then led a class discussion, or were asked to proceed directly to a class discussion. Because very little spaced testing research has used materials other than written text, we confined warm-ups to written materials. Warm-up questions were designed to serve three functions: (1) many warm-ups prompted students to explain previous content, thereby preventing misconceptions as they recalled and reaffirmed correct understandings of content. (2) Warm-ups served as a form of spaced testing. (3) Warm-up questions did just that—prepared students for the day's activities by reactivating previously covered content.

Spaced testing was also implemented via section quizzes given at the end of each chapter of the unit (five total). These included questions on the current chapter's content together with previous chapters' content. The latter typically connected with the big ideas of the unit, but some content was chosen because it was a topic/phenomenon associated with misconceptions.

Teacher self-report questionnaire data confirmed significant differences between conditions in diagram instruction, use of case comparisons, and use of spaced testing: across all units and cohorts, cognitive-science-based teachers used these more than content-only or business-as-usual control. This suggests that teachers did in fact implement the interventions as we intended.

Students participated in the study in their regular science classes and completed all of the regular textbook-based activities and tests included in the regular curriculum (as confirmed by teacher surveys). Integration of the interventions into the classes and curriculum was largely seamless; it is unlikely that students experienced the classes as participation in an experimental curriculum.

Overall, the intervention had several elements, but only one aspect was likely to directly influence ability to reason with diagrams and visualizations. The spaced testing may have improved retention of these newly acquired skills for test items that included visualizations and diagrams. These we consider as part of the overall visualization intervention (i.e., additional opportunities to practice visualization reasoning). Furthermore, by analyzing different diagram item types (e.g., directly instructed, uninstructed familiar content), we are able to show that the advantages of the cognitive-science-based instruction are not simply due to greater content knowledge.

Descriptions of the Conditions.

Content-Only Training (Hawthorne/Active Control) Condition. Teachers in the content-only training condition attended the same amount of professional development as the cognitive science teachers (3 days in the summer and four follow-up, after-school sessions for each unit). However, these sessions focused on the curriculum's underlying science content only, not on pedagogy or principles of learning. The training sessions were designed for teachers as adult learners and were provided by content experts who are experienced in implementing content-deepening training for teachers (e.g., university faculty, museum educators). These teachers did not receive any modifications to the standard curriculum. With regard to visual representations, the professional development materials contained many images (similar to a college-level course), but there was no explanation of how to understand the images or how to instruct students in understanding the images. The primary purpose of this condition in the current analyses was to rule out the possibility that student learning improvements in the cognitive science condition were due to a Hawthorne effect (i.e., improvements that stem from teacher *perceptions* of being actively involved in an experimental or higher quality condition) or participation in a teacher professional learning community that actively discussed the challenges of instruction with these units. Indeed, teachers in this condition self-reported that they enjoyed the training and that it was relevant to their classroom practices (despite the trainers avoiding making reference to teaching practices). However, the amount of content provided in this intervention is relatively modest and thus is not and was not intended to be a strong test of the benefits of teacher content knowledge on student learning.

When new teachers moved into a content-only arm school in the second year, they received makeup summer professional development and workshops during the school year, similar to that provided in Year 1. Returning content-only teachers were provided additional content training matched in duration to the follow-up training provided to the cognitive science teachers.

Students of teachers in the content-only training condition attended their scheduled science classes and completed only the activities included in the standard curriculum. After each given unit, students completed the relevant researcher-developed end-of-unit test that was standard to all three arms/conditions of our study.

Business-as-Usual Control Condition. Teachers in the business-as-usual control condition received neither professional development nor the modified curriculum. Prior to randomization of schools into conditions, they also consented to possible participation; teachers entering the study in control schools in later years were made aware of their participation within the larger study. Students attended their scheduled classes, completed only the activities included in the standard curriculum, and then completed our end-of-unit test.

For one Holt curriculum—*Inside the Restless Earth*—science teachers reported to us in continuing professional development that they had been asked to focus on reading and writing in their schools when Inside the Restless Earth was scheduled to be implemented. Hence, for Inside the Restless Earth we do not expect to see differences between conditions.

Materials and Procedure. Participants completed diagram comprehension items that were administered after a science content knowledge measure (see Porter, Polikoff, Barghaus, & Yang, 2013 for details of development) whose results are not analyzed here.

Diagram-Specific Items. Six sets of three diagram-specific items each were created for each curriculum and added onto the science content knowledge measure to create six unique test forms. These six test forms were then randomly given to students in the study.

With the exception of the Cells curriculum, which contained three additional diagram items but did not adhere to the following schema, each set of diagram items consisted of three item types. Two items from each set used diagrams taken directly from the curriculum, which were thus familiar to the students. Students of teachers in the cognitive-science-based condition were explicitly taught these diagrams in class, but students in the other two conditions had exposure to the diagrams through class reading assignments, textbooks, and other materials. One of these items in each set contained enough information on the diagram itself to be answerable—this item will be referred to as familiar stand-alone. The other familiar item in each set required students to recall an additional piece of information (either from the curriculum or in reference to the diagram itself)—this item will be referred to as familiar additional-context (for examples of these items, see Figure 1). The third item in each set featured a diagram that was taken either from other curricula that the students had not had, or, where necessary, was created by the research team. These items were in a science discipline that was unrelated to the curriculum. This question could be answered directly from information contained within the diagram, so this item will be referred to as unfamiliar stand-alone.

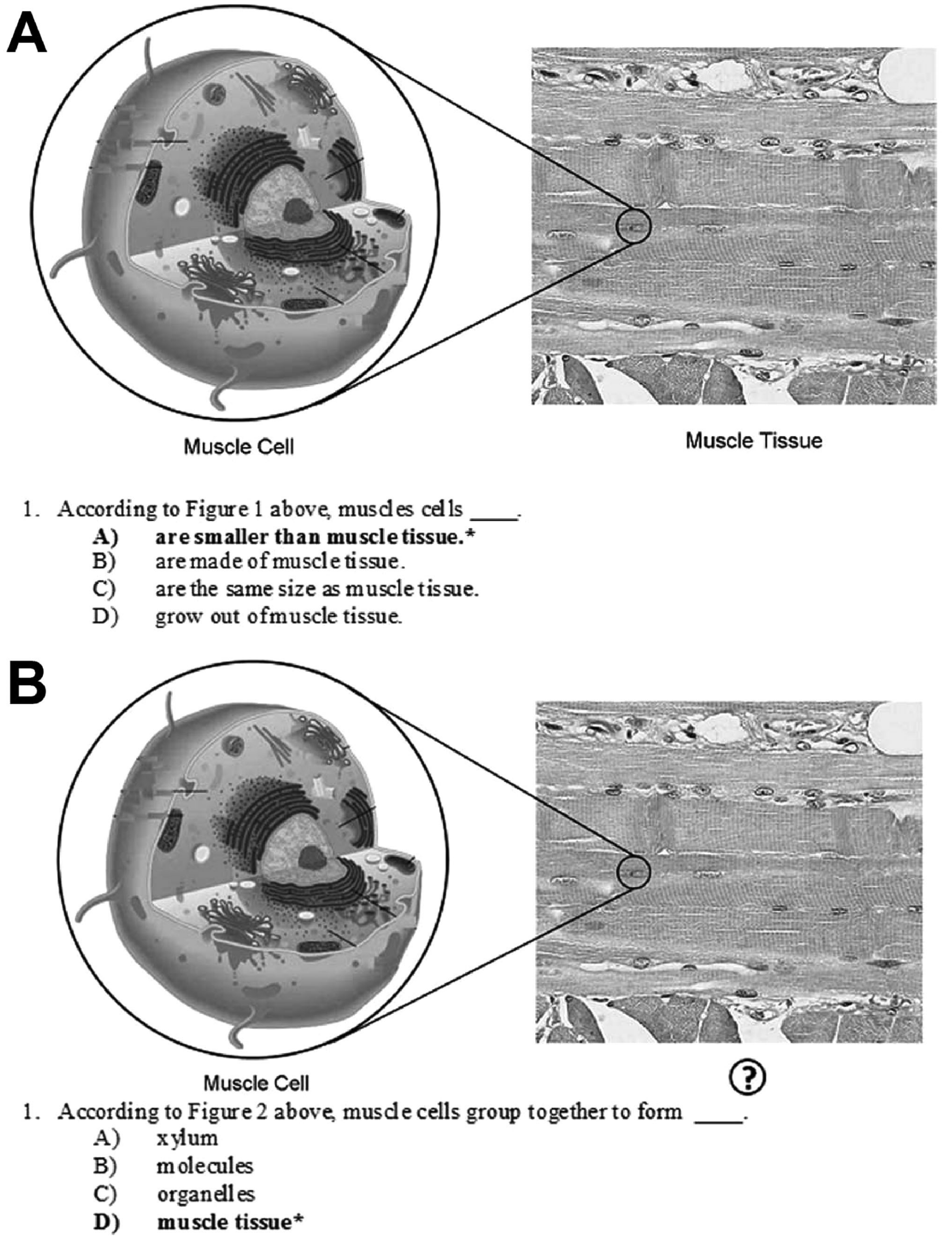
For the diagram items, reliability was calculated by first aggregating the data up to the teacher level for each individual item, and using the mean score per item of a teacher's classes from one year. Cronbach's α exceeded .83 for the three diagram items for all six curricula (range: .837 – .918). The added diagram items thus formed one cohesive factor, with performance on one diagram item strongly correlating with performance on the other two items. This suggests students generally relied on knowledge of diagrams to answer these items, whether or not the content was familiar or well understood.

Results

Our main hypothesis for end-of-unit diagram items was that students of teachers who received the cognitive-science-based intervention, which included targeted instruction for diagram conventions and interpretation, should perform better on these items. We conducted analyses at the teacher level because teachers were randomly assigned to an intervention group: business-as-usual control, content-only, and cognitive-science-based. We first focused on all three items together, regardless of item type, within individual curriculum units, to determine whether students in the cognitive-science-based classrooms outperformed the other classrooms on the diagram items overall.

First, we conducted a one-factor analysis of variance (ANOVA) with intervention condition as the factor. Of the five curricula for which the Cogsci intervention was implemented (Diversity of Life, Weather and Water, Earth History, Introduction to Matter, and Cells), all but Cells revealed significant effects of Condition (all ps $< .019$; see Figure 2 and Table 3). The significant omnibus ANOVAs were driven by different conditions across the curricula. Follow-up pairwise contrasts and effect sizes were calculated for each contrast separately, corrected for multiple comparisons with Hochberg's Bonferroni (Hochberg & Benjamini, 1990).

For the FOSS curricula, the cognitive-science-based condition consistently outscored content-only: for DOL, $d = 0.48$, for Weather and Water, $d = 0.49$, and for Earth History, $d = 0.62$. Targeted instruction in how to understand diagrams is associated with large classroom-level benefits on diagram-specific posttest questions, compared to simply increasing teacher content knowledge or generally including teachers in a professional learning community. The cognitive-science-based intervention also significantly outscored the control condition for two of the three units: for Diversity of Life, $d = 0.52$, and for Earth History, $d = 0.55$, but not for Weather and Water, $d = 0.41$. The third contrast between content-only and control conditions did not show any significant differences (all ps $>$ .05), suggesting that content professional development, although it included showing many diagrams, did not change student learning with diagrams.



1. According to Figure 1 above, muscles cells ____.
   - **A) are smaller than muscle tissue.***
   - B) are made of muscle tissue.
   - C) are the same size as muscle tissue.
   - D) grow out ofmuscle tissue.

1. According to Figure 2 above, muscle cells group together to form ____.
   - A) xylum
   - B) molecules
   - C) organelles
   - **D) muscle tissue***

Figure 1. Example of familiar stand-alone and familiar additional-context items. A familiar stand-alone item (A), and familiar additional-context item (B), taken from the Diversity of Life curriculum. Students in the cognitive science intervention saw this diagram in class. All test forms from all curricula contained both types of items (as well as an unfamiliar item), but never repeated the same diagram. Most diagrams were created to be familiar-stand alone and familiar-additional context and were administered to different students using different test forms.

Results for the Holt curricula were markedly different from those for the FOSS units and were somewhat different from each other. For Introduction to Matter, the cognitive-science-based condition significantly outscored content-only ($d = 0.52$), but not control ($d = 0.11$). The control condition significantly outscored content-only ($d = 0.44$). Cells and Inside the Restless Earth exhibited no significant advantages for any condition over any

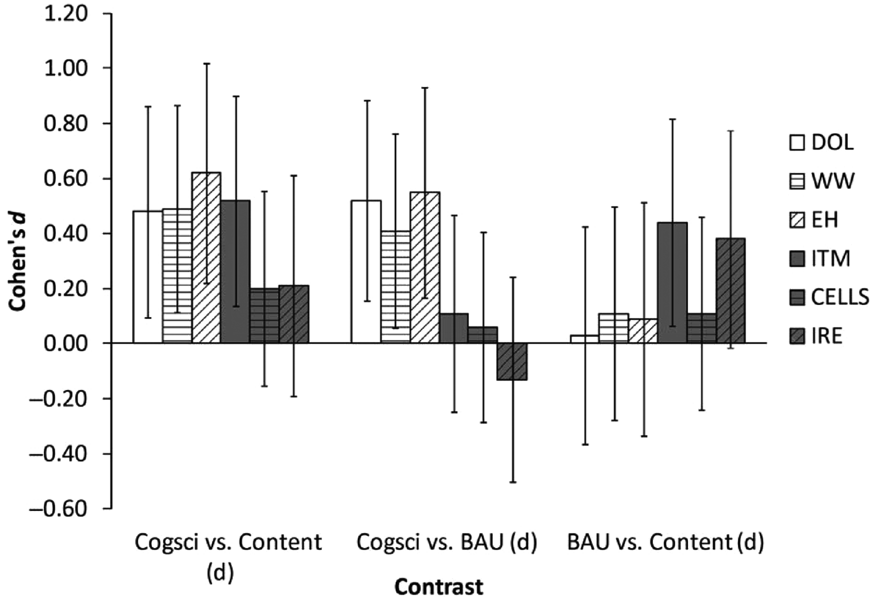


Figure 2. Effect sizes for contrasts between three intervention conditions conducted on all three diagram items. Effect sizes for each contrast, for all six curricular units. Error bars are 95% confidence intervals. Cogsci = cognitive-science-based condition; Content = content-only condition.

TABLE 3
Test Statistics for Six Curricular Units, All Three Diagram Item Types Combined

	Curriculum					
	FOSS			Holt		
Test	DOL	WW	EH	ITM	CELLS	IRE
Omnibus ANOVA (*F*)	5.36**	4.40*	16.82***	4.08*	0.51	1.62
(ω^2)	0.05	0.04	0.19	0.03	0.00	0.01
Follow-up contrasts						
Cognitive-science-based versus Content-only (*t*)	**2.54**	**2.63**	**2.86**	**2.69**	1.09	1.04
(*d*)	**0.48**	**0.49**	**0.62**	**0.52**	0.20	0.21
Cognitive-science-based versus Control (*t*)	**2.86**	2.31	**2.66**	0.62	0.35	–0.70
(*d*)	**0.52**	0.41	**0.55**	0.11	0.06	–0.13
Control versus Content-only (*t*)	–0.14	0.55	–0.02	**2.32**	0.62	1.99
(*d*)	0.03	0.11	0.004	**0.44**	0.11	0.38

Note: Uncorrected *p* -values for Omnibus test: $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. For follow-up contrasts, significant contrasts, surviving correction, are in bold. Numerator degrees of freedom for the omnibus ANOVA were two for all tests. For denominator degrees of freedom, refer to the number of teachers in Table 2. Negative values indicate effects in the reverse direction of the contrast.

other. Although combining data sets for different curricula must be done tentatively due to differences in overall curricular philosophy and in sample characteristics, for both teachers and students, we wanted to determine whether results for the Holt and FOSS curricula showed different patterns of results. Therefore, all data sets were combined, and a two-factor ANOVA was conducted with intervention condition as one factor with three levels, and data set (Holt or FOSS, with Cells and Introduction to Matter comprising Holt, and Earth History, Weather and Water, and Diversity of Life comprising FOSS). The interaction between intervention condition and curriculum producer was not significant, $F(2, 830) = 1.92, p = .15$. The main effect of intervention was significant, $F(2, 830) = 11.75, p < .001$, as was the main effect of curriculum producer, $F(1, 830) = 6.42, p = .01$.

Finally, all ANOVAs were repeated with prior year math and reading state scores normalized (by subtracting the mean of each state from each teacher's students' average scores and dividing by the standard deviation) and added into the model as covariates. In all models, prior math and reading scores were significant (whether in the model separately or together). With both math and reading scores added to the model, all effects of intervention condition that were significant before remained significant (Diversity of Life, Weather and Water, Earth History, Introduction to Matter). The pattern of results was the same with just math scores in the model. With just reading scores in the model, the effect of intervention for Weather and Water, $F(2, 171) = 2.64$, $p = .074$ and Introduction to Matter, $F(2, 167) = 2.43, p = .091$, became marginally significant. While prior achievement affects the posttest diagram scores, our intervention has a significant effect above and beyond prior achievement for three FOSS units and one Holt unit (Introduction to Matter).

Specific Diagram Item Types. We wondered whether effects were specific to a certain type of diagram item, or whether they generalized across the types of items. For example, an overall null effect could result from differential significant effects across already-taught and transfer items. As a reminder, in all but the Cells tests, the diagrams in the first and second test items had been previously presented in that exact form to students in the cognitive-science-based condition, and thus were both familiar to the students. The first diagram question was answerable directly from the diagram (familiar stand-alone), whereas the second required an additional piece of information to answer correctly (familiar-additional context). The third diagram was one the students had never seen before, but which could be answered directly from the diagram, requiring no additional context (unfamiliar stand-alone). To determine whether the effects of the cognitive-science-based intervention were specific to questions about diagrams that the students had been seen before, or generalized to new diagrams, we conducted separate ANOVAs within curriculum on each diagram item.

For the familiar stand-alone diagram items, the pattern of results was largely the same as the ANOVA on the combined items (see Figure 3 and Table 4). Across all three FOSS curricula, Diversity of Life, Weather and Water, and Earth History, each showed one intervention condition significantly different from one other (all ps < .042). The conditions in the two Holt curricula were not significantly different for Introduction to Matter, $F(2,168) = 3.05$, $p = .0502$, nor for Cells, $F(2, 186) = 0.36, p = .70$. Using Hochberg's Bonferroni corrected follow-up contrasts, the FOSS curricula exhibited an advantage of cognitive-science-based over either content-only or control, although due to reduced power, the significant contrast varied by curriculum. The contrasts revealed that, for the FOSS curricula, the cognitive-science-based condition consistently outscored the content-only condition on Weather and Water ($d = 0.46$), and Earth History ($d = 0.55$), but not Diversity of Life ($d = 0.37$). The cognitive-science-based condition significantly outscored the control group for Diversity

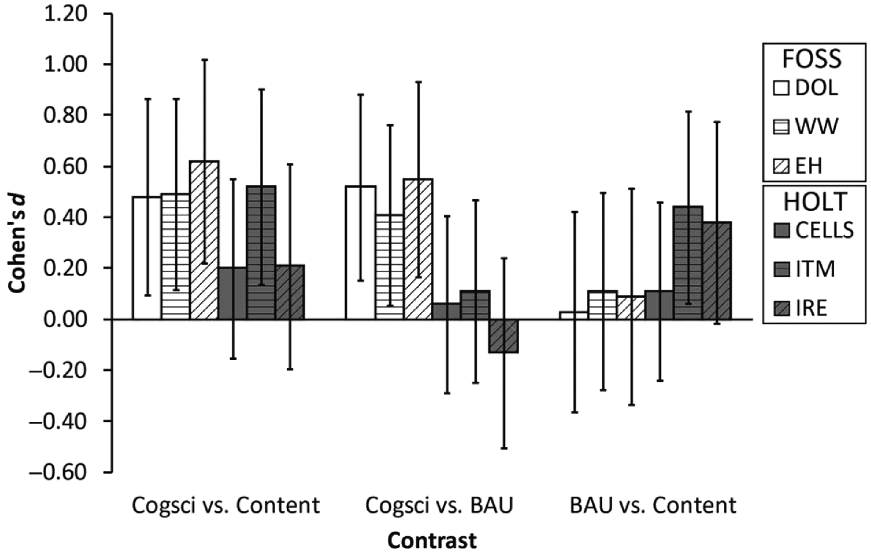


Figure 3. Effect sizes for contrasts between three intervention conditions conducted on the familiar stand-alone items. Effect sizes for each contrast, for all six curricular units. Error bars are 95% confidence intervals. Cogsci = cognitive-science-based condition; Content = content-only condition.

TABLE 4
Test Statistics for Six Curricular Units, Familiar Stand-Alone Items

	Curriculum					
	FOSS			Holt		
Test	DOL	WW	EH	ITM	CELLS	IRE
Omnibus ANOVA (*F*)	3.69*	3.92*	5.81**	3.05†	0.36	2.03
(ω^2)	0.03	0.03	0.07	0.02	0.00	0.01
Follow-up contrasts						
Cognitive-science-based versus Content-only (*t*)	1.94	**2.50**	**2.53**	2.29	0.94	1.82
(*d*)	0.37	**0.46**	**0.55**	0.44	0.17	0.37
Cogsci versus Control (*t*)	**2.47**	2.14	**2.99**	0.57	0.32	0.41
(*d*)	**0.45**	0.38	**0.62**	0.10	0.06	0.08
Control versus Content-only (*t*)	-0.49	0.62	-0.40	1.97	0.50	1.65
(*d*)	0.10	0.12	0.09	0.38	0.09	0.33

Note: Uncorrected *p* -values for Omnibus test: $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. For follow-up contrasts, significant contrasts, surviving correction, are in bold. Numerator degrees of freedom for the omnibus ANOVA were two for all tests. For denominator degrees of freedom, refer to the number of teachers in Table 1. Negative values indicate effects in the reverse direction of the contrast.

of Life ($d = 0.45$), and Earth History ($d = 0.62$), but not Weather and Water ($d = 0.38$). For these three curricula, the content-only and control conditions did not differ (all *p*s > .05). Finally, for Introduction to Matter, no contrasts exceeded the threshold of significance after correction. All other contrasts for the other curricula failed to attain significance after correction.

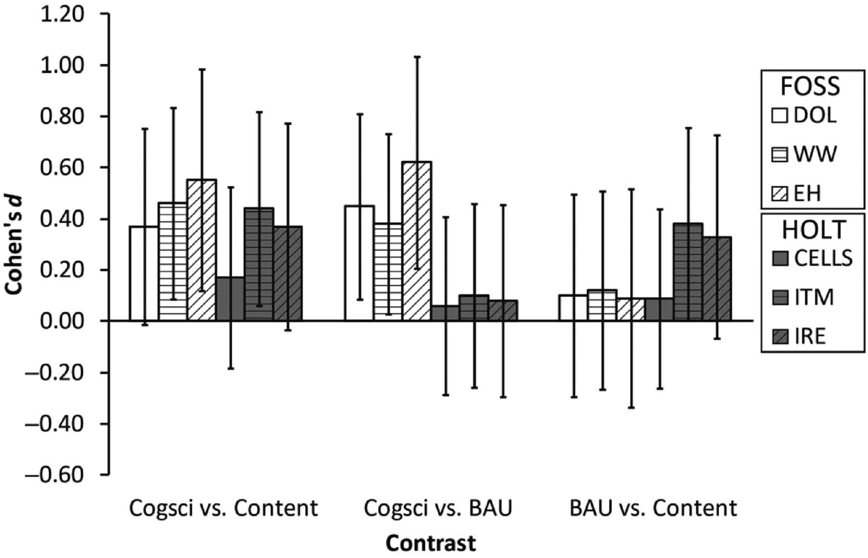


Figure 4. Effect sizes for contrasts between three intervention conditions conducted on the familiar additional-context items. Effect sizes for each contrast, for all six curricular units. Error bars are 95% confidence intervals. Cogsci = cognitive-science-based condition; Content = content-only condition.

For the familiar additional-context diagram items, the pattern was again very similar to the ANOVA on the combined items, but the effects were weaker across the board compared to the familiar stand-alone diagram items (see Figures 3 and 4). The pattern of performance for the conditions in Diversity of Life, Weather and Water, Introduction to Matter, and Cells were not different from the combined ANOVA, but the conditions were not significantly different across these curricula for familiar additional-context items. Only the one-factor ANOVA for Earth History was significant (see Figure 4 and Table 5). Follow-up contrasts, corrected with Hochberg's Bonferroni, reveal that the cognitive-science-based condition significantly outperformed content-only ($d = 0.73$) and control ($d = 0.66$). For all other curricula, the one-factor ANOVA was not significantly different between intervention conditions, (all ps $> .073$). However, analysis of the Cohen's d effect sizes for each curriculum reveals a similar pattern of performance with the cognitive-science-based condition outperforming content-only and control overall, despite the familiar additional-context items not reaching significance.

Finally, for the unfamiliar stand-alone items, the pattern of performance for the curricula remained consistent, but results were the strongest of those for the three item types. Diversity of Life, Weather and Water, Earth History, and Introduction to Matter had significant one-factor ANOVAs for the unfamiliar stand-alone items (all ps $< .02$), whereas Cells again did not (see Figure 5 and Table 6). For the FOSS curricula, follow-up contrasts corrected for multiple comparisons with Hochberg's Bonferroni revealed that the cognitive-science-based condition significantly outperformed both the content-only and control conditions (all ps $< .05$). Among FOSS curricula, the content-only and control conditions were not significantly different (all ps $> .05$). For the Holt unit (Introduction to Matter), the cognitive-science-based condition performed significantly better than the content-only ($d = 0.58$), as did the control condition ($d = .49$). However, the cognitive-science-based condition was not significantly different from the control group ($d = 0.09$).

TABLE 5
Test Statistics for Six Curricular Units, Familiar Additional-Context Items

	Curriculum					
	FOSS			Holt		
Test	DOL	WW	EH	ITM	CELLS	IRE
Omnibus ANOVA (*F*)	2.66	2.58	7.38**	1.85	1.07	0.87
(ω^2)	0.02	0.02	0.09	0.01	0.001	0
Follow-up contrasts						
Cognitive-science-based versus Content-only (*t*)	1.74	2.2	**3.36**	1.77	0.93	0.47
(*d*)	0.33	0.41	**0.73**	0.34	0.17	0.10
Cognitive-science-based versus Control (*t*)	2.16	1.53	**2.99**	0.09	-0.57	-0.84
(*d*)	0.39	0.27	**0.66**	0.02	0.10	0.16
Control versus Content-only (*t*)	-0.16	0.09	1.06	1.63	1.43	1.32
(*d*)	0.03	0.02	0.23	0.31	0.26	0.26

Note: Uncorrected *p*-values for Omnibus test: $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. For follow-up contrasts, significant contrasts, surviving correction, are in bold. Numerator degrees of freedom for the omnibus ANOVA were two for all tests. For denominator degrees of freedom, refer to the number of teachers in Table 1. Negative values indicate effects in the reverse direction of the contrast.

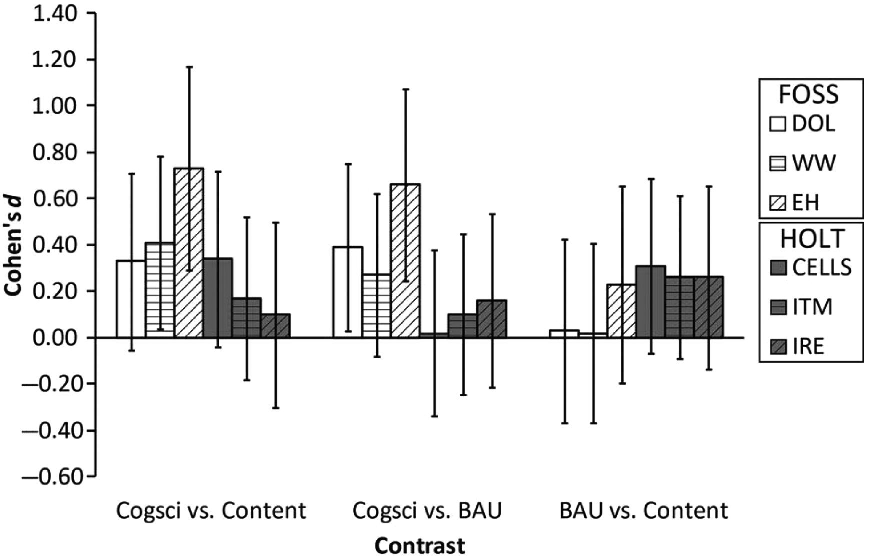


Figure 5. Effect sizes for contrasts between three intervention conditions conducted on the unfamiliar stand-alone items. Effect sizes for each contrast, for all six curricular units. Error bars are 95% confidence intervals. Cogsci = cognitive-science-based condition; Content = content-only condition.

Teacher Factors. As discussed elsewhere (Alfieri & Schunn, 2013), several factors appeared to significantly affect performance on the science content knowledge items for each curriculum, including (1) whether a teacher was teaching the material for the first time or the second time, and (2) underrepresented minority percentages of the classrooms. Because these factors are exploratory and not central to the question of efficacy of the

TABLE 6
Test Statistics for Six Curricular Units, Unfamiliar Stand-Alone Items

	Curriculum					
	FOSS			Holt		
Test	DOL	WW	EH	ITM	CELLS	IRE
Omnibus ANOVA (*F*)	6.83**	4.28*	4.59*	5.131**	0.61	1.82
(ω^2)	0.07	0.04	0.05	0.05	0.00	0.01
Follow-up contrasts						
Cognitive-science-based versus Content-only (*t*)	**3.16**	**2.36**	**2.71**	**3.02**	1.16	0.44
(*d*)	**0.60**	**0.44**	**0.59**	**0.58**	0.21	0.09
Cognitive-science-based versus Control (*t*)	**2.91**	**2.50**	**2.38**	0.90	0.33	-1.32
(*d*)	**0.53**	**0.45**	**0.49**	0.17	0.06	-0.25
Control versus Content-only (*t*)	0.36	0.09	0.39	**2.56**	0.71	2.05
(*d*)	0.07	0.02	0.09	**0.49**	0.13	0.41

Note: Uncorrected *p*-values for Omnibus test: $^{\dagger}p < .10$,$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$. For follow-up contrasts, significant contrasts, surviving correction, are in bold. Numerator degrees of freedom for the omnibus ANOVA were two for all tests. For denominator degrees of freedom, refer to the number of teachers in Table 1. Negative values indicate effects in the reverse direction of the contrast.

cognitive-science-based intervention in science curricula, we conducted two analyses separately instead of as part of the main ANOVA discussed above. We analyzed each factor separately by looking for interactions between performance overall and each of these factors.

Teaching Once or Twice. We wanted to determine whether there was a difference in receptivity to the interventions between teachers who taught the material in both cohorts and teachers who taught the material only once. To determine whether the pattern of results obtained in the one-factor ANOVA differed between groups of teachers, we ran the same ANOVA on the added diagram items but included two additional factors: whether the teacher Taught Twice[4] and Cohort. First, all six curricula had significant effects of Taught Twice. Teachers who ended up teaching the same curriculum twice significantly outperformed teachers who only taught the curriculum once (in either cohort; all *p*s < .013). Of the six curricula, Weather and Water, Diversity of Life, and Cells exhibited significant interactions between Taught Twice and Condition. All other interactions between Cohort, Taught Twice, and Condition were not significant. For the significant interactions, the pattern of performance was similar for Diversity of Life and Weather and Water. Teachers who only taught once matched teachers who taught twice only in the cognitive-science-based condition (Diversity of Life, $t[65] = 0.03$, $p = .98$; Weather and Water, $t[69] = 0.72$, $p = .47$). However, for Diversity of Life and Weather and Water, teachers who only taught once performed significantly worse in the content-only condition (Diversity of Life,

[4] Because Cohort is a separate factor, and because of the finding discussed in the next paragraph, we chose to code Cohort 1 teachers' scores as "Taught Twice" if they went on to teach the same curriculum in Cohort 2. Thus, the Taught Twice factor also includes teachers who had, at the time, yet to teach the curriculum a second time, but would the following year.

t[43] = 2.21, p = .03; Weather and Water, t[45] = 3.49, p = .001) and, for Diversity of Life but not Weather and Water, teachers who only taught once performed worse in the control condition (Diversity of Life, t[53] = 3.48, p = .001; Weather and Water, t[55] = 1.04, p = .30). Follow-up contrasts for Cells revealed a different pattern. Teachers who taught once performed worse in the cognitive-science-based condition, $t(61) = 2.05$, $p = .045$, similar in the content-only condition, $t(59) = 0.71$, $p = .48$, and worse in the control condition, $t(63) = 3.71$, $p < .001$. In short, teaching the unit twice led to better mean student scores for teachers in the cognitive-science-based condition (Cells) and content-only condition (Weather and Water and Diversity of Life).

Underrepresented Minority Status of the Classrooms. Previous analyses of the science content knowledge items from each curriculum had revealed differences in student performance depending on whether the classroom had a majority of underrepresented minority (i.e., black and Hispanic) students (Alfieri & Schunn, 2013). To determine whether these differences manifested in the added diagram items, we conducted a two-factor ANOVA with intervention condition as one factor and URM-status of the classroom as a second factor, using the same a cutoff of 90% URM students (Orfield, 2009).

Higher proportion URM classrooms performed worse than lower proportion URM classrooms on all five implemented curricula (all ps <.003). Out of the five implemented curricula, we found one significant interaction between intervention condition and URM status: Cells, $F(2, 183) = 4.16$, $p = .017$. For Cells, follow-up contrasts, corrected for multiple comparisons, reveal that cognitive-science-based teachers in lower URM proportion classrooms had significantly higher performance than cognitive-science-based teachers in higher URM proportion classrooms, $t(63) = 4.22$, $p < .001$, $d = 1.05$, whereas teachers from different URM status classrooms for the other two conditions were not significantly different. This pattern of performance is similar to the science content knowledge items for this curriculum (Alfieri & Schunn, 2013).

Discussion

The cognitive-science-based intervention appears to help these generally low-achieving students develop skills at answering questions that required them to use diagrams. The intervention was more successful in the FOSS curricula (Diversity of Life, Weather and Water, and Earth History) than in the Holt curriculum (Introduction to Matter alone). Furthermore, the intervention was more successful in classrooms that were not extremely segregated—even after controlling for prior academic achievement—and in classrooms where the teacher was teaching with our interventions for the second time, suggesting some practice in implementing the diagrammatic interventions is useful. We will unpack these differential effects in the general discussion.

Many randomized controlled trials, and indeed much of the literature on smaller scale classroom interventions, show effects on researcher-developed tests but not on standardized tests, which are less susceptible to confirmation bias. In the state for which our Holt curriculum study took place, we were able to obtain Cohort 2 item-level data for student performance on the statewide standardized science test administered 1 year after our intervention. In Study 2, we analyze effects of the three experimental conditions on performance on diagram items from this standardized test. It is possible that the consistent exposure to the interventions across three units will produce effects even though the effects were small on the researcher-developed posttests for each unit.

TABLE 7
Student-Level Demographics for Students Providing State-Mandated Test Scores

Variable	*n*	Percent
	3,443	100
Treatment		
Control	1,344	38.6
Content-only	860	24.7
Cognitive-science-based	1,275	36.6
Sex		
Female	1,718	50.1
Male	1,743	49.4
Race		
URM*	2,660	76.5
Non-URM	801	23.0
	M	*SD*
Age (months)	164.1	5.9

Note: URM group includes Hispanic, Black, American Indian, and Others.
Non-URM group includes Asian and White.

STUDY 2

To further test the effects of our intervention, we examined group differences between cognitive-science-based, content-only, and control conditions in performance on a subset of questions—the ones using diagrams—from one state-required standardized science test, which the Holt student participants took in their eighth-grade year in 2011 (i.e., 1 year after participating in the intervention). The specific hypotheses were as follows:

1. Classrooms in the cognitive-science-based condition will outscore those in the content-only and control conditions on state science test items on items that require reasoning with diagrams (necessary-sufficient-diagram items), after accounting for demographics.
2. Classrooms in the cognitive-science-based condition will outscore those in the content-only and control conditions on state science test items on items that require reasoning with diagrams and require bringing basic science knowledge to bear (necessary-not-sufficient-diagram items); however, effect sizes may be smaller for necessary-not-sufficient-diagram items, after accounting for demographics.

Method

Participants. Participants were from the schools that participated in our intervention who were taught with only the Holt Curriculum by 105 participating science teachers and whose state test items we were able to analyze. We obtained the standardized science test scores for 3,443 eighth-grade students who had participated in our intervention the previous year when they were in seventh grade. For the purpose of analysis, classes were split into less-segregated (< 90% URMs in the classroom) and more-segregated (90% or more URMs in the classroom). (See Table 7 for detailed demographic information about the participants.)

TABLE 8
Number and Reliability of Diagram Items Coded from the 2011 State Science Test

Diagram Necessity for an Item	Code	Number of Items	α
Unnecessary and distracting	0	1	n/a
Unnecessary	1	3	.513
Helpful, not necessary	2	4	.596
Necessary, not sufficient	3	7	.748
Necessary and sufficient	4	10	.803

*Cronbach's alpha on teacher-level data.

Measures.

State Science Test. The state-required science test was developed by a professional test company for the state where the research took place, all items were validated on students in the state, and the test was mandatory for all eighth-grade students in public schools in that state. The test was high stakes for each school, in that the school could be sanctioned if student scores did not increase from year to year, but there were no consequences for student performance. The content of the test is based on the state content standards for eighth grade (i.e., the content involved in Introduction to Matter and Inside the Restless Earth, but not Cells), and it is a standards-based, criterion-referenced assessment that combines multiple-choice response format with brief and extended constructed response items. The test score levels (i.e., advanced, proficient, basic, below basic) provide an understanding of student performance related to the attainment of proficiency of the academic standards and are used to assist teachers in identifying students who may need additional learning opportunities.

Selection of Diagram Items. The first, second, third, and fourth authors independently coded all multiple-choice questions on a secure copy of the test and came to 100% agreement on which items included diagrams, and how necessary and sufficient the diagrams were to answering the question (0 = unnecessary and distracting, 1 = unnecessary, 2 = helpful but not necessary, 3 = necessary but not sufficient, or 4 = necessary and sufficient).[5]

Subscale reliability was calculated by first aggregating the data up to the teacher level for each individual item, and using the mean score per item of a teacher's class. Cronbach's α were .513 ~ .803 for the four types of diagram items (Table 8). For the purpose of examining the effects of the intervention on students' ability to use diagrams to solve science problems, the analysis of the present study was on the 7 test items that had a diagram which was necessary but not sufficient ($\alpha = .748$) and the 10 test items that had a diagram or diagrams which contained *necessary and sufficient* information to solve the problem ($\alpha = .803$).

Procedure. Consistent with state regulations, students were administered the state science test by their own classroom teacher in an untimed session expected to take 50– 60 minutes in their regular classroom in Spring 2011. Students were given an individual booklet containing test questions on which they recorded their own answers in pencil, together

[5] ANOVAs with the same covariates were also conducted on distracting item, unnecessary-diagram items, and helpful-unnecessary items, and there were no significant group differences found in these scores. However, due to the unacceptable reliability of scores for these relatively few diagram items (see Table 8), we do not present or further discuss the detailed findings about these diagram items.

TABLE 9
Descriptive Statistics: Sum Scores of Necessary-Sufficient and Necessary-Not-Sufficient Diagram Items

		Necessary-Sufficient		Necessary-Not-Sufficient	
Intervention	Number of Classes	*M*	*SD*	*M*	*SD*
Control	39	4.6	1.2	3.6	0.8
Content-only	30	4.1	0.9	3.3	0.8
Cognitive-science-based	36	5.0	1.3	3.8	1.0
Total	105	4.6	1.2	3.6	0.9

with a science reference sheet containing information such as metric-to-English conversion factors. Booklets were sent to a central state location for scoring, and the item-level scores were provided electronically to the research team using a secure unique student identification number. In addition to the eighth-grade item-level state test scores, the states provided us with reading and math scores on the state tests from the year previous to each year of the intervention.

Results

Our main hypothesis was that students who were taught in the seventh and eighth grades by the teachers who received the Holt cognitive-science-based interventions in 2010 should perform better on the two types of diagram items (i.e., necessary-not-sufficient-diagram and necessary-sufficient-diagram items) in the state science test at the eighth grade in 2011. We conducted analyses at the teacher level, because the mostly single-teacher schools were randomly assigned to an intervention group: control, content-only, or cognitive-science-based.

The teacher-level descriptive statistics are presented in Table 9. In general, students performed at a low-to-medium level on both types of diagram items: scoring about 4.6 of 10 points on the necessary-sufficient-diagram items, and about 3.6 of 7 points on the necessary-not-sufficient-diagram items.

We conducted analysis of covariance (ANCOVA) on sum scores of (1) the 7 necessary-not-sufficient-diagram items and (2) the 10 necessary-and-sufficient-diagram items, to examine differences between control, content-only, and cognitive-science-based groups, controlling for the effects of student age, sex, and race.[6] These three variables were found by prior research to have significant influences on differences in performance on standardized test scores (e.g., Trends in International Mathematics and Science Study [TIMSS], 2011; Mullis, Martin, Ruddock, O'Sullivan, & Preuschoff, 2009), which we accounted for by including them in the ANCOVA model as covariates.

Necessary-Not-Sufficient-Diagram Items. Levene's test of equality of error variances showed that the homogeneity assumption was not violated ($F[2, 99] = 0.417, p = .660$). ANCOVA results indicate no significant differences between control, content-only, and cognitive-science-based groups ($F[2, 99] = 2.176, p = .119$, partial $\eta^2 = .040$), controlling

[6] Other demographic variables—English Language Learner, disadvantaged, and disability—were not entered as covariates into the ANCOVA model due to unequal variances between groups.

TABLE 10
ANCOVA Between-Group Comparison on Necessary-Sufficient-Diagram Items

Source	*df*	*F*	Significance	Partial η^2
Intercept	1	24.687	<.001	.221
Age	1	18.365	<.001	.156
URM	1	38.678	<.001	.281
Female	1	3.239	.075	.032
Treatment	2	4.364	.015	.081
Error	98			

TABLE 11
ANCOVA Model Parameter Estimates for Necessary-Sufficient-Diagram Items

					95% CI		
Parameter	*b*	*SE*	*t*	*p*	Lower	Upper	partial η^2
Intercept	31.530	5.873	5.368	<.001	19.876	43.183	.225
Age	–0.153	0.036	–4.285	<.001	–0.224	–0.082	.156
Female	0.825	0.458	1.800	.075	–0.085	1.734	.032
URM	–2.193	0.353	–6.219	<.001	–2.893	–1.493	.281
Treatment							
Control	–0.495	0.220	–2.247	.027	–0.933	–0.058	.049
Content-only	–0.642	0.233	–2.753	.007	–1.105	–0.179	.071
Cognitive-science-based	0[a]						

[a]This parameter is set to zero because it is the baseline.

for the effects of age, URM, and female (see Table 10). All three covariates had significant effects on performance on necessary-not-sufficient items (b_{Age} = –0.138, t = –5.201, p < .001, partial η^2 = .215, b_{Female} = 773, t = 2.281, p = .025, partial η^2 = .05; b_{URM} = –1.638, t = –6.278, p < .001, partial η^2 = .05; see Table 11).

Necessary-Sufficient-Diagram Items. Levene's test of equality of error variances showed that the homogeneity assumption was not violated (F[2, 102] = 0.336, p = .715). There were significant differences between control, content-only, and cognitive-science-based groups (F[2, 99] = 7.653, p = .015, partial η^2 = .081), controlling for the effects of age, URM, and female (see Table 11 for detailed ANCOVA between-group comparison results). Although the effect size was small, it was well above the "recommended effect size representing a 'practically' significant effect" (Ferguson, 2009, p. 533).

The effects of treatment on necessary-sufficient-diagram items were above and beyond three covariates—age, sex, and race. As shown in Table 11, the covariates age and URM had significant negative effects, whereas female showed a nonsignificant effect on student performance on necessary-sufficient-diagram items. After accounting for these covariates, cognitive-science-based groups significantly outperformed the control (b_{control} = –0.495, t = –2.247, p = .027, partial η^2 = .05) and content-only conditions (b_{content} = –0.642, t = –2.753, p = .007, partial η^2 = .07), with effect sizes that indicate practically important findings (Ferguson, 2009). The control and content-only groups did not significantly differ from each other in answering the necessary-sufficient-diagram items (see Figure 6 for estimated marginal group means).

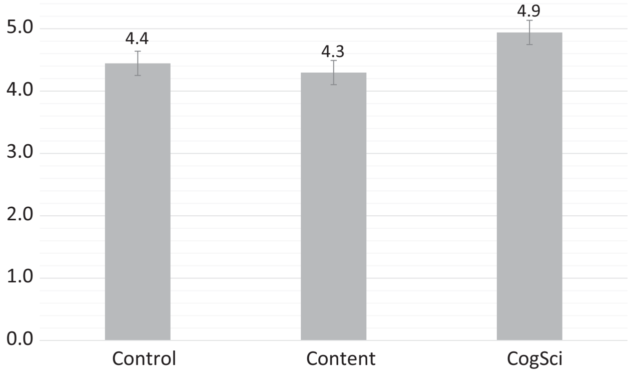


Figure 6. Estimated marginal group means on necessary-sufficient-diagram Items. Standard errors are represented in the figure by the error bars attached to each column.

Discussion

In Study 2, we found the same pattern of results as in Study 1: The cognitive-science-based intervention was associated with better scores, this time on state standardized test items. The items that were responsive to our intervention were the necessary-and-sufficient items, which require the very diagram skills that were instructed in this intervention. There were no group differences on necessary-not-sufficient items, suggesting that a higher intensity of instruction or a different type of instruction would be required before students could engage in this more difficult reasoning (e.g., Gobert & Clement, 2009, were able to obtain increases in higher order reasoning with diagrams using a more intensive drawing-to-learn intervention). Although we found effects of demographic covariates, the cognitive-science-based intervention advantage held even after accounting for those covariates.

GENERAL DISCUSSION

In the present research, we have shown that curricular modifications based on principles of instructing visualization conventions can be implemented by regular middle-school classroom teachers with modest amounts of training, to yield positive effects on students' basic reasoning with diagrams. We were able to find these results on researcher-developed measures that might be expected to be more tightly aligned to what was taught, as well as on a commercially developed state test that we as developers had not seen before designing the modifications.

In Study 1, we replicated results from Alfieri and Schunn (2013) on science content knowledge items, by showing that high-URM classrooms benefited slightly less on the Cells diagram posttest in the cognitive-science-based intervention (compared to low-URM classrooms). The advantage of teaching in a condition twice versus once was also replicated across almost all curricula and conditions (with the exception of an advantage for teaching Cells once), consistent with many randomized controlled trials in education. The advantage for lower URM (below 90%) is not due to differences in prior achievement; the differences remained even after accounting for prior math or reading scores. The differences might be due to concentrated poverty at the class level, which is known to be associated with less academic time on task, due to various types of disruptions (e.g., time taken up with sharing limited resources, classroom management).

With regard to 1 year versus 2 years of teaching in the cognitive-science-based intervention, teachers apparently developed enough skills, knowledge, and familiarity (e.g., metarepresentational competence; diSessa, 2004) with our visualization exercises during initial and ongoing professional development to use them when teaching, but a second year of implementation led to larger student gains. This might be due to fluency in giving initial explanations, more detailed knowledge of student weaknesses and potential misunderstandings of visualizations, developing more ways to scaffold student learning with the materials, or other development between the first and second year of implementation. The greater gains by the second year of implementation is pragmatically important: As is common in work with large urban school districts, we observed a high level of teacher "churn," with many participating teachers moving to different schools or moving to teach different subjects in the same schools after 1 year. Research has consistently associated teacher churn with lower student achievement. We were able to show significant and relatively large effects despite the high level of churn in our study, but the effects were even larger—and the promise of the intervention is greater—when teachers are able to remain teaching science for 2 years in a row in the same school.

The different pattern of results across familiar stand-alone, familiar additional-context, and unfamiliar stand-alone items suggests that benefits come from both better understanding of how to read diagrams and also from greater content knowledge (Won, Yoon, & Treagust, 2014). Recall that for directly instructed familiar stand-alone items, students in our cognitive-science-based intervention had an advantage over the content-only group in Earth History and Weather and Water, and over the control group in Earth History and Diversity of Life: all three groups saw the diagrams in their textbooks but only the cognitive-science-based condition received instruction in how to make sense of them. For the more cognitively challenging familiar additional-context items, the cognitive-science-based group advantage held for Earth History only, suggesting that the cognitive-science-based intervention was appropriately targeted at building the most basic diagram comprehension skills. The unfamiliar stand-alone items, by contrast, required diagram skills to be applied to completely new science content (Schönborn & Bögeholz, 2009), and here we saw the cognitive-science-based group advantage across both comparison groups on all three FOSS units and one Holt unit.

Although many educational interventions can produce results on researcher-developed items such as those in Study 1, improving student performance on standardized tests is known to be more difficult (see, e.g., Rosenshine & Meister, 1994). Strikingly, despite the fact that end-of-unit tests had shown scant effects in the traditional curriculum units, in Study 2 we found that our cognitive-science-based intervention yielded significant effects on diagram-specific items from a state exam administered 1 year after our intervention. These effects were seen on items that require reasoning with diagrams, even after controlling for demographics. State exam questions that require combining text (e.g., a description of an experiment) and diagrams (a drawing of the experimental setup) are likely very difficult for students to answer unless they know how to make sense of the diagrams (Cook et al., 2008), and this is exactly the skill that is instructed in the cognitive-science-based instruction. One possible explanation for finding effects on a delayed statewide test but not on a researcher-designed end-of-unit test is that teachers may have continued teaching the diagram comprehensions skills in the subsequent grade in the intervening year—despite much churn between schools, most students remain within the school district. Future work could assess this possibility with direct measures of carryover.

Limitations

Despite the large sample size, our study does have a number of limitations. First, we do not have a true test of the *Inside the Restless Earth* unit, given the low level of implementation by teachers. On the one hand, the learning tasks appear to be the most conceptually difficult of the *Holt* units; on the other hand, it does not appear to be as difficult as the *FOSS Earth History* unit, on which we were able to show numerous significant effects (see Tables 3 and 5). Second, the activity-focused *FOSS* units and the textbook-focused *Holt* units are qualitatively different from each other, but we do not have the kind of detailed classroom observations that would explain *how* that activity versus textbook focus interacted with our cognitive-science-based treatment. Such observations could also help us understand different ways that teachers used to the provided materials (e.g., specific scaffolding provided to students, specific examples used), and possible different sources of effectiveness of the materials. Third, the state high-stakes test was taken one full year after the interventions, and there might be confounding variables affecting these test scores, such as teachers continuing to provide diagrams instruction within the same schools after the intervention was over. Fourth, the response formats for the state test are more varied—e.g., include constructed responses—and possibly more difficult—e.g., include diagram + table + graph representations—than our end-of-unit tests, making it difficult to compare results from the two.

Findings from laboratory studies do not always translate into successful classroom interventions (Hulleman & Cordray, 2009); not only are school-aged children different from the typical undergraduate research participant, but the learning environment is much less controlled than laboratory conditions, and teachers delivering interventions have many other responsibilities than do research assistants working one-on-one with participants in a lab or in pullout training studies done in schools. Despite the differences between the conditions in the basic research literature that we built on and the large-scale classroom intervention we delivered, the principles of visualization comprehension do in fact transfer to the "blooming, buzzing confusion of classrooms" (Brown, 1992). This suggests that there are at least three strong regularities of visualization comprehension across this growing body of basic research and applied research on visualization comprehension: (1) making sense of visualizations—these recent cultural products—is not effortless and self-evident, and the process frequently breaks down; (2) students who receive supports for comprehending visualizations can improve their comprehension; and (3) the learning can transfer to new domains. Finally, our study shows that classroom science teachers without a degree in cognitive psychology can learn to effectively provide instruction and scaffold learners in the process of visualization comprehension, which leads to improved performance of a meaningful magnitude on both researcher-designed and standard-based criterion-referenced based state tests. These findings imply, in turn, that science teachers can instruct students in *how to* comprehend diagrams as part of the curriculum; in the present research and in recently published studies, such efforts involved some professional development. Furthermore, teachers might expect smaller gains in the first year of directly teaching diagram comprehension and larger gains in the second year. In addition, they might expect larger gains in less-segregated classrooms. Second, such instruction can be beneficial beyond the directly instructed diagrams, including both diagrams that represent instructed content and possibly those that use the same conventions to represent novel content.

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