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Learning Physical Science through Astronomy Activities: A Comparison between Constructivist and Traditional Approaches in Grades 3-6

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Abstract

We report on an evaluation of the effectiveness of Project ARIES, an astronomy- based physical science curriculum for upper elementary and middle school children. ARIES students use innovative, simple, and affordable apparatus to carry out a wide range of indoor and outdoor hands-on, discovery- based activities. Student journals and comprehensive teacher materials aid in making the science content accessible to students based on their shared experiences and observations. Approximately 750 Grades 3–6 students in ARIES (or treatment) classrooms are compared with approximately 650 Grades 4–6 students in control classrooms through a series of open-ended assessment measures, using a pretest and posttest format. A detailed analysis by item measures the gain in treatment and control groups. We identify concepts where the ARIES approach is more effective, where both are equally effective, and where neither results in much learning. (The ARIES approach was never less effective.) Although learning is in evidence for both control and treatment groups, overall, the ARIES students achieve roughly four times the gain of their control counterparts. In particular, ARIES students had much greater gains for the concepts that the control students found most difficult.

1. INTRODUCTION

For the last two decades, many organizations both within and outside the science education community have mustered support for major changes in elementary and middle school science curricula and teaching methods. The most widely known reports that focus specifically on science teachers and science teaching include *Before It's Too Late* (National Commission on Mathematics and Science Teaching for the 21st Century 2000), commonly known as the "Glenn Report"; *Standards for Science Teacher Preparation* (National Science Teachers Association 1998); the *National Science Education Standards* (National Research Council 1996); and *Benchmarks for Science Literacy* (American Association for the Advancement of Science 1993). Science educators and scientists at the Science Education Department (SED) of the Harvard-Smithsonian Center for Astrophysics (CfA) responded to this need by developing new, discovery-based curricula for elementary and middle schools. The National Science Foundation (MDR 91-54113 and ESI 95-53845), with support from Harvard University and the Smithsonian Institution, funded the development and implementation of Project ARIES from 1991 to 2002. ARIES is aligned with national and many state standards, and in particular, there is nearly complete overlap between ARIES and the attributes of science education needing "greater emphases" called for in the NSES (Ward, Catledge, & Price 2005). ARIES draws on contemporary research on how children learn and the most effective pedagogical strategies to engage children in active learning. Many observers agree that one of the best ways to improve elementary and middle school science education for all children is to increase the amount of discovery science done in schools (Driver 1994; Etheredge & Rudnitsky 2003; Grennon Brooks 2002; Harcombe 2001; Kober 1993). New materials must have broad appeal to both teachers and students if this goal is to be reached (Loucks-Horsley et al. 1998). ARIES materials have been designed to appeal to Grades 3–8 teachers who are not now using discovery-based curricula, as well as to those who are experienced with that approach.

The unifying theme of ARIES is astronomy. It links together the curriculum's eight self-contained modules. Half of the modules focus on space science or astronomical themes, and the other half deals with physical science themes (in this, article, "physical science" means physics and chemistry only). Each module includes numerous intercurricular and multicultural extensions—that is, activities connecting the science lessons to other subjects such as mathematics, reading, or art, and to the astronomical models of ancient or non-Western cultures. ARIES modules were field tested in more than 100 schools nationwide. Teachers generally use a module for 14–18 weeks when science is taught twice weekly. For many reasons, astronomy represents an ideal, but often underused, resource for involving more children of diverse backgrounds and abilities in learning physical science. Much of astronomy is on the frontier of scientific discovery and in the news daily, and many aspects have terrestrial analogues that provide tangible and observable experiences for people of any age. Although many of the key ideas of ARIES are embedded in astronomy, these ideas transcend astronomy and can be understood by everyone. It is a visual science whose phenomena are experienced every day. Although children are familiar with many of these phenomena—such as the rising and setting of the Sun, the seasons, or the movement of the Moon and its phase changes— they still continue to provoke curiosity and awe. Yet these phenomena are often counterintuitive, and many students continue to hold on to models of these phenomena that are inconsistent with observations of those phenomena.

The SED has been contributing to the reform of science curricula and science teaching in the nation's schools for more than 20 years through the development of innovative, research-based curricula along with standards-based assessment strategies. The department is a unique community of scientists and educators who work together on projects linking research, technology, curriculum development, student learning, professional development, and assessment. The success of the SED in developing effective and popular curriculum materials results from its forging highly committed teams of scientists and educators. These teams have placed a special emphasis on projects for elementary and secondary students, all with links to age-appropriate mathematics. Much has been learned through these projects about the science skills and knowledge of elementary and middle school students and teachers. The SED's first curriculum, Project STAR (Science Teaching through its Astronomical Roots), is a high school astronomy curriculum. The STAR philosophy—to identify student preconceptions and then to build up understanding of concepts through discovery activities—has helped shape all the curriculum and professional development projects that have followed. The emphasis in ARIES, as in STAR, has been on identifying the misconceptions of students and then on developing materials and teaching strategies to help the students reconstruct their understanding in accord with the behavior of the natural world. There is a listing of some of the SED materials at the end of this article.

In the remainder of this article, we describe the philosophy and logic undergirding the ARIES program (Section 2); the teachers, schools, and classrooms involved in the assessments of learning from the treatment (or ARIES) and control groups, as well as the test instruments used (Section 3); the statistical basis of the data analysis and the results obtained (Section 4); a comparison of the assessment outcomes between the two groups and an interpretation of these findings (Section 5); and the conclusions we draw from this study as well as general remarks about the ARIES curriculum (Section 6).

2. DEVELOPMENT OF ARIES

Three interrelated themes shape the ARIES curriculum: (1) research into children's misconceptions, (2) research into how people learn, and (3) science content that is accurate, accessible to students and teachers, and limited to major concepts of physical science and space science. The SED has long been investigating and documenting how students' misconceptions persist in spite of some of the very best science teaching. The department's research on how misconceptions block learning was documented originally in its Science Media Group's award-winning video, *A Private Universe*. More recently, the *Minds of Our Own* series shown on PBS reinforced those findings, showing how students' prior beliefs remain impediments to deeper understanding of the natural world even in the face of compelling evidence or observations inconsistent with these ideas. ARIES uses discovery-based explorations and classroom teaching strategies as a way to help students reexamine their personal models of the natural world. When the students' predictions do not match their findings, they are most open to reassessing and changing their personal beliefs.

Most people have a wide range of misconceptions about physical and space science phenomena. Deeper understanding of these phenomena is often counterintuitive. SED researchers have examined K–16 students' beliefs about concepts such as Moon phases, the seasons, Earth's orbit and spin, acceleration, energy, waves, light, color, and more. Many students, even those at the college level, continue to hold on to models that are inconsistent with nature regardless of the number of science courses they have taken. The learning approach embedded in ARIES is often broadly defined as constructivism. Constructivism focuses on ways to help children alter their personal views of everyday phenomena based on evidence from observations of nature (Ausubel 1968; Diakidoy & Kendeou 2001; Driver 1983; Novak 1993; Roth 1989; Yager 1991). It holds that learning is meaningful and useful when it helps learners make better sense of the world around them. The constructivist approach to learning has grown out of cognitive research. The research of Piaget (1929, 1953) gave perhaps the greatest impetus to the widespread studies of student misconceptions carried out over the last 40 years (McDermott 2006; Minstrell & Kraus 2005; Posner et al.

1982; Vosniadou 1991). Broadly stated, this approach holds that knowledge is idiosyncratic and is constructed by learners; it is not something that can generally be given directly to students by a teacher. Students come to class with ideas about the world constructed from their everyday experiences and the influence of others, yet many of these ideas contrast sharply with the behavior of nature. It is necessary for students to make sense of, or to justify in their own words, the models constructed by others. In spite of years of formal education, students hold strongly to their alternative views, often because they have never had to explicitly test them. The pedagogy of ARIES helps students to question their intuitive views or models. Where the models are not supported by their observations, the latter can provide the reason or entrée for students to rethink their ideas.

ARIES is a curriculum that is both scientifically accurate and readily accessible to students and teachers in the elementary classroom. We believe that children need to build up a set of skills, or intellectual tools, that will help them look at the natural world in a productive and meaningful way. As a start, the scope of the science curriculum needs to be limited, which for elementary and middle school students means examining or studying a few concepts from multiple perspectives rather than trying to look at each of many concepts superficially. Further, science lessons chosen must be of interest to the students and related to their everyday experiences. We believe that students' conceptual growth and the processes of science go hand in hand; the processes cannot be construed as entities onto themselves, but rather are to be used by students in developing their understanding of concepts. These twin pillars of learning are embedded in the ARIES student science journal, a part of every module.

An ARIES module consists of a teacher resource binder, a science journal for each of 30 students, and a bin of specialized apparatus, enough for 15 two-student teams. The teacher resource binder includes complete science, history, and pedagogy background notes, classroom strategies for effective implementation of ARIES, tips for adult helpers, a sky-viewing packet for the astronomy modules, intercurricular extensions, and detailed assessment suggestions that include a pretest/posttest comprising open-response questions and scoring rubrics for the questions. The pedagogical approach of ARIES is carefully built into the student science journal. Each exploration or activity begins with an elicitation of the students' prior ideas and their own original questions that are recorded in their journals. The second section of the journal is the procedure portion. This section includes a list of the required materials, a step-by-step procedure with space for students to record predictions, observations, and data, and additional space to organize data in diagrams, tables, or graphs. The final section includes questions and an embedded assessment component encouraging students to justify their ideas about what they have learned. Although many explorations can be done with materials commonly found in classrooms, some require specialized materials that are included in the apparatus bins for each module. Fuller descriptions of the modules and ordering information can be found on the publisher's Web site: http://www.charlesbridge.com/.

3. COMPARISON TESTING

ARIES staff conducted a comparison study of student understanding of the concepts addressed in three modules: (1) Exploring Time: Sundials, Water Clocks, and Pendulums; (2) Exploring Light and Color: Filters, Lenses, and Cameras; and (3) Exploring the Earth in Motion: Daylight, Sun, and Shadow Patterns. The evaluation was a collaborative effort between project staff and an outside evaluator with an extensive background in assessment. Dr. Marcus Lieberman, president of Responsive Methodology of Albuquerque, New Mexico, with assistance from Annette Trenga at the SED and the authors, managed the study. Ms. Trenga handled the logistics of test distribution and scored the open-ended items blind to the classrooms involved. Dr. Lieberman recruited classrooms and performed the statistical analysis of the test results. The study was carried out in 31 elementary and middle-school classrooms and involved approximately 750 students in 15 classrooms using ARIES materials, and approximately 650 students in 16 control classrooms. The study was designed to test two research hypotheses: (1) students in classes using ARIES materials will significantly increase their understanding of concepts related to time, astronomy, and light and color, and (2) students in classes using ARIES materials will increase their understanding of concepts related to time, astronomy, and light and color significantly more than students in control classes studying the same subjects but not using ARIES materials.

Our evaluation team originally contacted 25 teachers who had participated in regional ARIES institutes and invited those able to do so to take part in the comparison evaluation. A total of 15 agreed to participate. Each of the 15 volunteer teachers in the ARIES classrooms had participated in at least one SED teacher enhancement institute. Eight of these 15 teachers had participated in field testing of the three modules used in this study. Four teachers were using ARIES for the first time with their students. There were ARIES classrooms (Grades 3–6) in urban (4), suburban (9), and rural (2) schools. The numbers of students tested in each setting were 96, 535, and 131, respectively.

Teachers integrated different ARIES modules into their classroom curricula at different times over the course of an academic year; as a result, ARIES students were pretested and posttested at varying times during the school year. The teachers then submitted logs or schedules listing the actual dates of instruction and testing. We included scores only for those students who completed both the pretest and the posttest for a specific module. In most cases, an individual teacher used only one of the modules and in several cases did not complete the module. As a result, the number of valid treatment pretests and posttests for any item varies considerably, reflecting this nonuniform implementation. Evaluators observed ARIES classes or interviewed teachers to confirm that the curriculum was being taught as modeled by the developers in the professional development institutes. In all cases, the observers found the instruction to be a faithful implementation of the pedagogy in ARIES.

The 16 control classrooms (Grades 4–6) were in urban (2), large suburban (1), and small suburban (1) schools. The numbers of students tested in each setting were, respectively, 239, 390, and 27. All the control classrooms were in communities with at least one ARIES classroom in the same community, and six of the control classrooms were in the same building as an ARIES classroom. Students in the control classrooms studied the same major concepts as the ARIES students. The concepts included the nature and cause of shadows and outdoor shadow patterns; apparent daily motion of the Sun and its changing path across the sky from season to season; day and night and the changing hours of daylight and darkness from season to season; light and its role in vision; scattering and reflection of light; color; lenses; and the refraction of light. The control students took the pretest in the fall. The posttest was given in the spring so the control students had ample opportunity to cover all the same concepts as the ARIES students. We included only those scores of control students who completed both a pretest and a posttest. Unlike the varying numbers of valid pretests and posttests for the treatment group, the number of valid control pretests and posttests for each item is constant because only a single test is involved. None of the 16 control teachers had ever worked with ARIES materials, and none used the materials during the year. All control schools except the small suburban school had significant minority student populations (< 50%), as did six of the ARIES schools.

Before constructing the test instrument used in the study, we asked the control classroom teachers for curriculum guides detailing the scope and sequence of their science programs. When a curriculum guide did not exist, the evaluators provided a checklist of concepts or topics addressed in the ARIES modules, asking the teachers to note which of the concepts or topics on the checklist they taught their students. Concerned for fairness and the minimization of bias, we chose only those items for which participating teachers assured us that the control students would study the same concepts or topics during the school year as the ARIES students. For the comparison study, we then constructed a 17-item "sampler test" using questions from the ARIES tests for each module. The sampler test was given as both a pretest and a posttest (see the appendix for the complete test).

All test items are open-ended, constructed-answer questions. None of the items is module specific. Classroom teachers and science educators reviewed the test items to assure that all the questions could be understood by children in Grades 3–6. The constructed-answer feature of the questions makes it possible for students to demonstrate both their answers and how they arrived at their answers. The ARIES and control teachers returned completed tests to the evaluation office for scoring. The evaluators developed a scoring rubric for each question in order to assess the range of student understanding for all the concepts addressed. Four people scored the tests. The evaluators tested the scoring procedure, comprising the scoring rubrics for all the questions, for interrater reliability. The reliability between scorers was < 0.90; it is a rate of agreement considered acceptable for this type of assessment.

4. DATA AND RESULTS

The major statistical test used in this study is a paired comparison *t*-test. We use the *t*-test to find if the growth from pretest to posttest in either the treatment or control group is significant. If the significance is ≤ 0.05, we use it as an indication that the difference between the distribution means is not likely due to chance but to some intervention between the pretest and posttest (i.e., that it is statistically significant). One must not confuse statistical significance with the magnitude of the effect. We calculated the effect sizes for each item and for the total score. The effect size denotes the gain of an intervention or treatment in units of standard deviations.

In Table 1, we report the results, by item and then aggregately, for the two student populations. The themes addressed by question are: 1a–3: cause of shadows, outdoor shadow patterns, and time; 4–5: indoor shadow patterns; 6: day and night; 7: magnetism; 8: daily path of Sun; 9–10: orientation of Earth to Sun; 11–12: vision and light; 13–14: scattering and reflection of light; and 15–16: prisms and refraction of light. The numbers of ARIES students vary. This variation reflects the fact that some teachers completed only a portion of a module.

The data show an increase in score for every item in both the control and ARIES groups. For the ARIES group, gains were significant ($p \leq 0.05$) for all but one item (#12). For the control group, gains were significant for all but three items (#5, #9, and #11). For the ARIES group, gains were significantly greater than gains for the control students for all but two items (#12 and #14). The overall data show that ARIES students both (1) significantly increased their conceptual understanding of the materials taught and (2) significantly outperformed students in control classes in which the same topics were taught without ARIES.

Table 1. Normalized Results for Control (C) and ARIES Students (T)

Module	Item Name		# of Students	Mean Score			Standard Deviation		Standard Error		Effect Size			
				Pre	Post	Gain	Pre	Post	Pre	Post	Value		SE	ARIES Advantage
Time	(1a) Making Shadows	C	506	0.60	0.69	0.09	0.26	0.19	0.01	0.01	0.34	***	0.05	
		T	298	0.57	0.86	0.29	0.26	0.17	0.01	0.01	1.13	***	0.07	***
	(1b) Making Shadows	C	506	0.57	0.78	0.21	0.50	0.41	0.02	0.02	0.42	***	0.06	
		T	298	0.46	1.00	0.54	0.50	0.00	0.03	0.00	1.08	***	0.06	***
	(2) Outdoor Shadows to Tell Time	C	506	0.13	0.18	0.05	0.16	0.17	0.01	0.01	0.35	***	0.06	
		T	159	0.08	0.30	0.22	0.14	0.10	0.01	0.01	1.41	***	0.10	***
	(3) Shadow Predictions	C	506	0.31	0.43	0.12	0.33	0.35	0.01	0.02	0.32	***	0.06	
		T	159	0.50	0.82	0.32	0.40	0.28	0.03	0.02	0.87	***	0.09	***
Astronomy	(4) Flashlight Shadows – 1	C	506	0.44	0.58	0.14	0.45	0.45	0.02	0.02	0.32	***	0.06	
		T	159	0.59	0.90	0.31	0.42	0.26	0.03	0.02	0.71	***	0.09	***
	(5) Flashlight Shadows – 2	C	506	0.18	0.22	0.03	0.39	0.41	0.02	0.02	0.08		0.06	
		T	159	0.32	0.73	0.41	0.48	0.45	0.04	0.03	0.94	***	0.11	***
	(6) Night and Day	C	506	0.41	0.61	0.20	0.49	0.49	0.02	0.02	0.42	***	0.06	
		T	68	0.29	0.59	0.29	0.46	0.50	0.05	0.06	0.62	***	0.18	*
	(7) Making a Compass	C	506	0.11	0.15	0.04	0.25	0.28	0.01	0.01	0.16	**	0.07	
		T	73	0.16	0.58	0.42	0.26	0.38	0.03	0.04	1.68	***	0.20	***
	(8) Sun's Path	C	506	0.14	0.24	0.10	0.25	0.31	0.01	0.01	0.38	***	0.07	
		T	73	0.25	0.58	0.33	0.28	0.40	0.03	0.05	1.25	***	0.20	***
	(9) Earth Terminator	C	506	0.10	0.11	0.01	0.23	0.24	0.01	0.01	0.05		0.06	
		T	50	0.32	0.76	0.44	0.28	0.29	0.04	0.04	1.73	***	0.20	***
	(10) Seasons	C	506	0.04	0.08	0.05	0.21	0.27	0.01	0.01	0.22	**	0.07	
		T	50	0.04	0.38	0.34	0.20	0.49	0.03	0.07	1.66	***	0.37	***

Light and Color	(11) Objects in a Dark Room	C	506	0.34	0.36	0.02	0.47	0.70	0.02	0.03	0.04		0.08	
		T	183	0.34	0.77	0.43	0.47	0.43	0.03	0.03	0.91	***	0.10	***
	(12) Objects Emitting Light on Their Own	C	506	0.48	0.53	0.05	0.42	0.40	0.02	0.02	0.13	*	0.06	
		T	183	0.45	0.47	0.02	0.40	0.40	0.03	0.03	0.06		0.10	
	(13) Path of Light	C	506	0.16	0.24	0.08	0.28	0.30	0.01	0.01	0.27	***	0.06	
		T	183	0.29	0.56	0.27	0.33	0.38	0.02	0.03	0.88	***	0.11	***
	(14) Mirror and Flashlight	C	506	0.48	0.54	0.06	0.40	0.41	0.02	0.02	0.15	**	0.06	
		T	181	0.76	0.84	0.08	0.33	0.30	0.02	0.02	0.21	*	0.10	
	(15) Prism	C	506	0.18	0.22	0.05	0.24	0.25	0.01	0.01	0.19	**	0.06	
		T	114	0.25	0.36	0.12	0.25	0.23	0.02	0.02	0.49	***	0.12	**
	(16) Pinhole Image	C	506	0.16	0.27	0.11	0.25	0.30	0.01	0.01	0.34	***	0.07	
		T	90	0.39	0.94	0.56	0.38	0.22	0.04	0.02	1.79	***	0.12	***
Overall	Mean Control	C	506	0.28	0.37	0.08	0.33	0.35	0.06	0.06	0.25	***	0.06	
	Mean Treatment	T	50–298	0.36	0.67	0.32	0.34	0.31	0.06	0.06	1.02	***	0.14	***

Statistical significance of the effect sizes of or between treatment (T) and control (C) groups is noted as *($p \leq 0.05$), **($p \leq .01$), ***($p \leq .001$).

In Figure 1, we plot, by item and then in aggregate, the effect size of the mean gain. The error bars represent one standard error of the effect size. The overall effect size for ARIES students (1.02) was slightly more than four times greater than that of the control group (0.25). Where the error bars intersect between control and ARIES classrooms, we conclude that there was little difference between the two groups. The items in the first portion of Figure 1 (1a–3) are drawn from the ARIES time module, items in the middle portion (4–10) are drawn from the first astronomy module, and the remaining items (11–16) are drawn from the module on light and color.

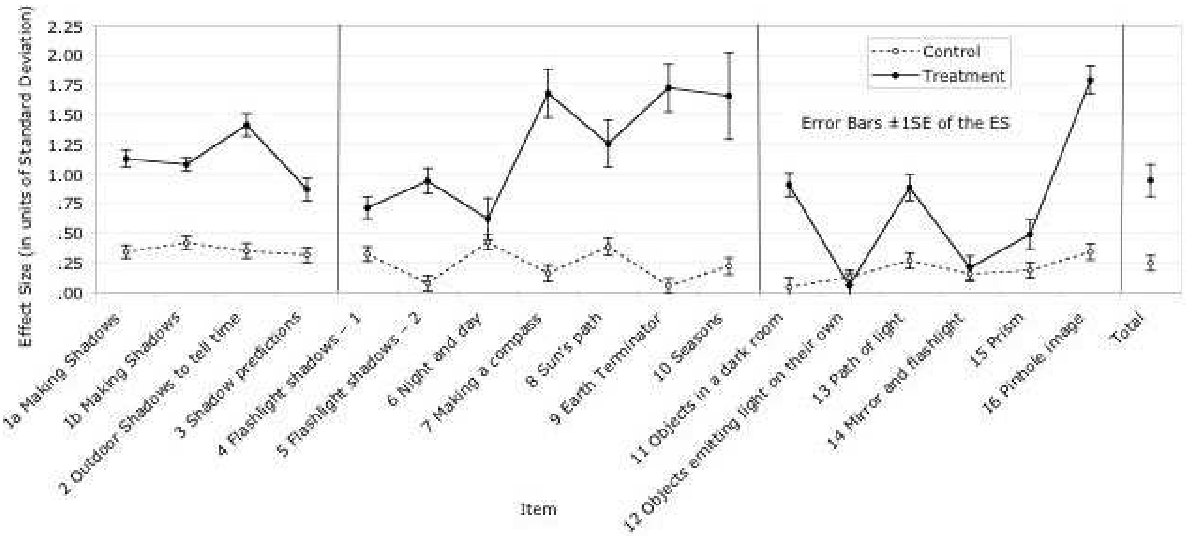

Figure 1. Effect Size of Mean Gain by Item for ARIES and Control Students

5. ANALYSIS AND DISCUSSION

Each ARIES module includes a sequence of hands-on explorations requiring direct observations of nature's behavior, and classroom activities in which students model natural phenomena. Understanding shadow phenomena, both inside and outside, plays a critical role in several ARIES modules. In the module on time, it is the predictable, repeating patterns of outdoor shadows produced by the students' Plaster of Paris gnomons that lead to the use of sundials for finding the time of day. The same outdoor shadow patterns provide evidence of the changing orientation of Earth to the Sun at different locations in Earth's orbit and provide a foundation for building a model to understand the reasons for seasons. Students can also infer that Earth's surface is curved or determine the direction of Earth's spin by comparing outdoor shadow patterns with the shadow patterns observed on the model spherical Earth in the curriculum's astronomy lab. Light and color phenomena are central to astronomy and to many portions of the ARIES curriculum. The light and color module used in the ARIES classrooms includes explorations to investigate emission, reflection, and refraction of light, and the effect of prisms on light. In the discussion to follow, we will examine what classroom and curriculum factors might contribute importantly to the gains seen in the tests.

5.1 Shadows and Time

Elementary school students often carry out activities involving shadows, particularly shadows cast by objects in sunlight. ARIES students progress toward a systematic investigation of how the shadow of a vertical gnomon changes size and orientation over the course of a school day. The difficulty experienced by students in understanding such shadows is twofold. Students generally think of shadows as concrete entities that do not vary (Apelman 1984). When asked if their own shadow exists when they are in the dark, students commonly say "yes," with the caveat that light is necessary to see it. Students often think of shadows as always being the same size as the original object, and always "behind" it. Multiple shadows are not thought to exist, and shadows must always be connected to the casting object. These beliefs are so strong in students that they reject frequent evidence of changing shadow size and direction, as well as multiple shadows. We see what we believe. The second major difficulty is making the connection between an illuminating source and a shadow. Although students can trace out a gnomon's shadow (or their own) over the course of a day, seeing the Sun's changing position as responsible requires a different coordination of these several representations with this far-away orb in the sky. The ARIES students use a "suntracker," described in section 5.2, to link the Sun's changing position to outdoor shadow changes.

ARIES students did considerably better on all the shadow-related items (1a–5, 9), with gains between three and six times greater than the gains made by the control students. What might be the cause of this large difference in achievement? The ARIES students spend considerable time observing and investigating shadow behavior. Outdoors, the students predict and explore the constantly changing direction and length of shadows, initially through the course of one day, then from week to week, and eventually from season to season. Indoors, they explore the relationship between the shapes of objects and their shadows as the orientation changes between the objects, light sources, and surfaces on which the shadows are cast. These investigations generally later help ARIES students to develop a deeper understanding of how shadows form and what can be learned from the outdoor shadow patterns about the spin and orbit of Earth. The pretest data show that Items 5 (flashlight-produced shadows) and 9 (Earth terminator) were moderately difficult, with less than a third of the students in both groups answering the items correctly. Item 2 (outdoor shadows to tell time) was even more difficult than Items 5 and 9. For Items 5 and 9, the ARIES students made significant gains, outperforming the control students on both questions by considerable margins. This difference can most likely be traced to the extensive time spent modeling shadow behavior, particularly when using the astronomy lab. This shoebox-sized lab has a number of viewing ports, permitting students to observe how the day-night terminator is oriented on the model Earth at different times of the year. Students are also able to compare outdoor shadow patterns with those they create in their labs.

Understanding how to use outdoor shadows (Item 2) to tell time remained elusive for both groups. ARIES students gained more than the control students did; nonetheless, the ARIES group's mean posttest score is the lowest of all the items. We sense that the differences here between the two groups are to be traced to the emphasis on the shadow activities, which is integral to ARIES. However, in spite of this emphasis, the ARIES students did not score highly, even after making and using sundials. The cognitive ability to transfer the concrete shadow patterns to the more abstract concept of using these patterns to keep or find the time may be too subtle or difficult for Grades 4–6 students and may be better addressed in later grades.

5.2 Daytime Astronomy

The understanding of the day-night and the seasonal cycles is built on an understanding of the motions within the Sun-Earth system and the pattern of illumination of Earth by the Sun. Students often confuse Earth's orbit and its spin, with many thinking that Earth orbits the Sun in 24 hours (Sadler 1998). Seasonal changes are commonly viewed as resulting from Earth's (slightly) elliptical orbit rather than from the nearly constant direction in which Earth's axis points as Earth moves about the Sun (Sadler 1992). Learning about day/night and seasons often requires a rethinking of a student's previously held ideas. For ARIES students, changes in the Sun's path through the sky over many months, particularly the lowering angular height throughout the fall season, demand explanation. ARIES students explore the illumination of a model Earth in the astronomy lab to reveal phenomena that other students may also commonly experience; for the ARIES students, it is more clearly an off-planet point of view. For many ARIES students, these activities both confront student preconceptions and offer a plausible, more powerful model for predicting phenomena.

In Item 8, students are asked to draw the path of the Sun across the sky for summer and winter. The ARIES students' improvement after instruction can most likely be traced to a set of explorations done in the astronomy module. Students build "suntrackers" to track the angular height above the horizon and the compass direction of the Sun from hour to hour over the course of a day. They repeat these measurements several times throughout the year. They then graph these data to show how the path of the Sun changes from week to week, or season to season. Before ARIES students construct the suntrackers, they make their own magnetic compasses, beginning first by exploring the behavior, in a variety of settings, of a bar magnet suspended on a string, and then coupling it with a compass rose to fashion a working magnetic compass. By contrast, other students are traditionally given magnetic compasses and provided little opportunity to investigate the properties of magnets used in constructing such compasses. The pretest scores show that Item 7 (constructing a compass) was difficult for both groups and that the ARIES students did significantly better than their control counterparts on the posttest. We tentatively trace this difference to the discovery approach used in the ARIES curriculum and the fidelity with which the curriculum is used by the teachers.

The question on seasons, Item 10, was very difficult for both groups prior to instruction. It remained just as difficult for the control students after instruction; although the ARIES students showed considerable gain after instruction, their mean posttest score was still lower than the results for all but Item 2. The ARIES module used in this study does not fully address the reasons for seasons, focusing instead on the exploration of the evidence for the constantly changing orientation of Earth's spin axis with respect to the Earth-Sun direction throughout the year. Outdoor shadow patterns provide some of the evidence; students also model this changing orientation in the astronomy lab. Item 10 asks students to describe what makes the number of daylight hours change from summer to winter for most places on Earth. Here, as in Item 2, the transfer between concrete data and an abstract concept appears limited; incorporating their observations into a model for the seasonal change in daylight hours appears to be difficult for many Grades 4–6 children. In fact, in ARIES, the reasons for seasons is only fully addressed in a module targeted primarily for students in Grades 7 and 8.

For the question on night and day, Item 6, students are asked to describe what causes night and day on Earth. Each group shows significant gains on the posttest scores for this item. It may be that modeling night and day is something done extensively in most elementary and middle school classrooms, or perhaps it is something that children have previously understood. ARIES students model night and day in the astronomy lab, even investigating the differing number of daylight and nighttime hours from season to season. Results here suggest that many of the children did not incorporate a spinning Earth into their model for night and day, even with the use of discovery-based materials, as in the case of the ARIES students. Or, like many Grades 4–6 children, students in this study may have persisted in holding onto the belief that the Sun orbits Earth once a day and that this is the cause of night and day.

5.3 Light and Color

Light and color themes are commonly studied in elementary and middle school classrooms. All these phenomena were included in the courses of study of the control schools. In aggregate, the gains for both groups were lower for items in this category than for those in the two prior categories.

Here we address the light and color items in order. In Item 11, students are presented a list of five brightly colored or reflective objects and asked to identify which of the objects could be seen in a totally dark room. Pretest scores suggest that this is a moderately difficult item prior to instruction for both groups.

But, similar to several of the items analyzed earlier, after instruction, the control students show marginal gains, while again, the ARIES students increased their posttest scores significantly. What in the ARIES experience might account for this difference? The ARIES light and color module includes several explorations in which students convert their light lab (similar to the astronomy lab) into a light-tight box. The box has a viewing port to look inside. When students place a hood over their heads and the box, they can look inside without letting outside light enter. Given a number of brightly colored and reflective objects, the students are asked to predict which of the objects can be seen in the light-tight box. Students also take turns placing objects in the light-tight boxes for identification by other classmates. We have observed children doing this exploration in the classroom; when they discover that none of the objects is visible, the comments heard most often are those of incredulity. It is likely that an Aristotelian model of vision, in which light moves from one's eye to an object, persists for a large proportion of the control students and a smaller number of ARIES students. The persistence of this model for seeing is well documented in *Minds of Our Own,* the SED's program noted earlier. For others, it may be that the classroom explorations are not yet powerful enough to counter the common everyday experiences for which people are able to see things in very dark rooms, which they take to be totally dark.

In Item 12, students are asked to select from a list of objects those that give off light of their own. Pretest scores suggest that this is not a difficult task, with little change for either group between pretest and posttest. Upon re-examination, we believe that this item was poorly worded. Some students we interviewed after the posttest drew distinctions between sources of natural light (such as a firefly) and artificial light (such as a light bulb). As a result, they bundled together objects, such as the human eye and mirrors, with artificial light sources, believing that none gives off light of its own (although other students may have selected the eye as a source of its own light, as postulated in the preceding paragraph).

For Item 13, students were to indicate the paths that light would travel for one to see an apple illuminated by a flashlight. This item remained difficult for the control students even after instruction. The stronger posttest scores for ARIES students are likely to be associated with the great number of explorations that they do with flashlights and the light lab. This item is subtler than the prior two items in that students need to draw the "light rays" from the flashlight to the apple, and then back to the eye. Moreover, although students may experience looking into a light-tight box and not being able to see objects within, no one has actually seen light rays reflect from an object such as an apple. Many students had rays going to the apple from one's eye and then bounding back into the eye (i.e., not including any "light rays" from the flashlight). A few students created a ray pattern from the flashlight to the apple back to the flashlight. Others had single rays going to the apple from both the flashlight and the eye. The misconception that one's eye emits light in order to see objects was the most common incorrect answer, particularly for the control group.

The mirror and flashlight question (Item 14) was relatively easy for both groups. The gains after instruction were nearly equivalent. To correctly answer the item, students needed to show that the light beam striking a flat mirror at an angle was reflected from the mirror at the same angle. The most common incorrect answer in each group was one in which the light reflection was shown to be perpendicular to the mirror's surface. We sense that students select this answer because it is associated with the experiences one has when standing in front of a mirror. Item 15 about prisms remained moderately difficult for both groups after instruction, with modest gain for the ARIES students and minimal gain for the control group. Incorrect responses included everything from having only one color of light emerge as a result of the white light passing through the prism, to having the colored light disperse in random directions. Although the student answers from both groups suggested that most realized white light passing through a prism was changed in some way, the more subtle characteristics of the dispersion pattern of the colored light is a difficult concept for younger children. One of the more common misconceptions children hold is that "white" light has no color and that a prism adds colors to the light.

The last question, Item 16, is related to the orientation of an image formed when the scattered light from an object (in this case, a pine tree) passes through a pinhole onto a screen. Although the image would be both inverted and reversed, an answer was counted as correct if only the image was inverted. The ARIES student gains were very large and their posttest score very high, exceeded by only one other item. The control students improved marginally after instruction. We associate this difference between the two groups with the explorations done by the ARIES students with the light lab. The lab is converted first to a pinhole camera and is then improved by affixing a lens. When first using the pinhole model of the lab, essentially a camera obscura, nearly all the students are surprised to see the image on the screen inverted. They repeatedly turn their labs over, trying unsuccessfully to get the image inside to be upright.

5.4 Comparison of Control and ARIES Groups by Item Difficulty

In Figure 2, we plot, by item, the mean posttest score against the mean pretest score for both the control and ARIES students. The straight lines, fit by ordinary least squares, for the two sets of data show gains for both groups, with the gains of the ARIES students greater than the gains of the control students. The straight-line fit for the control group is a significantly better representation of the data than the corresponding fit for the treatment group as characterized by the R^2 value of variance (e.g., the fraction of variance explained). Gain for the control group was small for all items, whereas it ranged from small to large for the ARIES group. Additionally, ARIES students show much greater gains on the more difficult items (i.e., Items 2, 5, 7–11, 13, and 15, each with a pretest mean score < 0.33).

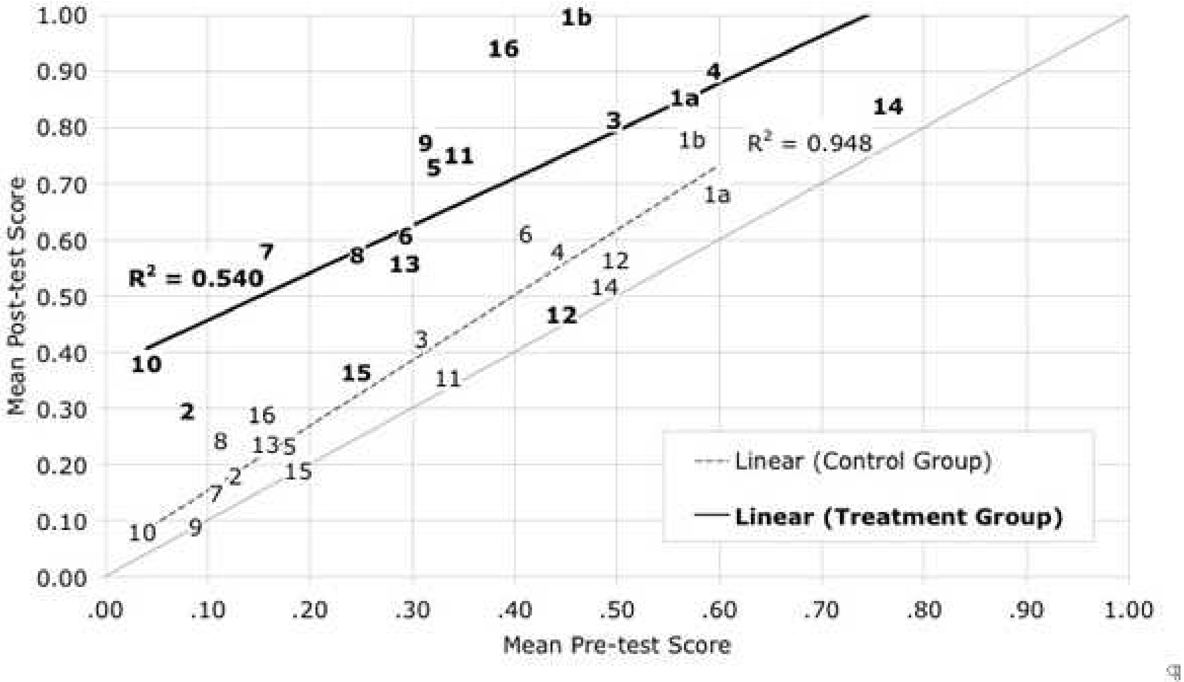

Figure 2. Mean Posttest Scores vs. Mean Pretest Scores for ARIES and Control Students

The data points on Graph 2 reflect the mean pretest and posttest scores, item by item, with the dashed line representing data for the control students and the bold line representing data for the ARIES students. Extended upward, these two trend lines would intercept at the point at which the gains for both groups are equal. The items near this point are the easier items as defined by the relatively high pretest scores. Conversely, the gains on the more difficult items (again, defined by the pretest scores) are significantly greater for the ARIES students than for the control students. Based on the pretest scores (< 0.13) of both groups, Items 2, 7, and 10 were the most difficult; taken together, the ARIES student gains on these items were slightly more than four times greater than the control student gains.

6. CONCLUSIONS

The results of this comparison study suggest that overall, the ARIES discovery-based constructivist curriculum yields increased learning for Grades 3–6 students studying physical and space science concepts compared with Grades 4–6 students in control classrooms. This difference is particularly pronounced for concepts shown by pretest scores to be most difficult for both groups prior to instruction, with the posttest gains of the ARIES students being much greater than the posttest gains of the control students. Because this study was preliminary and not explicitly funded, we could not control all relevant variables that could influence the results. These variables include (1) detailed student demographics, (2) self-selection of the ARIES teachers, (3) teacher qualification, background, and experience, (4) school and/or district factors, such as school size and class size, (5) the curriculum materials used in the control classrooms, (6) the starting date and total time spent by each group on each major concept, and (7) professional development institutes that teachers attended. For most of these factors, we have no knowledge of even the sign of any possible bias introduced into our results. However, based on hints from this study and data reported elsewhere (Ward et al. 2005), it is possible that any one of these factors may have had a positive role in the increased learning for the ARIES students, but likely not nearly enough to overcome the disparity in learning between the ARIES and the control groups.

Both ARIES and control classrooms showed very poor gains on some items. This result may reflect intrinsic problems with the assessment item or that the concepts are developmentally inappropriate for upper elementary students. The approach and materials used in ARIES classrooms appear to have little to recommend them over those used in control classrooms for three concepts: the cause of night and day, how a flashlight and a mirror interact to reflect a spot of light, and how a prism and a flashlight interact to produce colors. The ARIES activities may not be sufficiently more effective than the usual classroom activities to warrant replacing them.

The choice by teachers to use ARIES, even those using the curriculum for the first time, may reflect confidence in using a pedagogical approach that draws on students' prior ideas, predictions, and original questions to shape the classroom discourse. Such a choice is significant because it is well documented that many Grades 3–6 teachers are underprepared in pedagogical methods emphasizing proficiency in scientific inquiry, subject competence, and skill in actively engaging students (Hestenes 2000; Paige 2002; Weiss et al. 2001, 2003). It is also likely that embedded in this choice is a degree of general confidence in teaching physical and space science. Compared with earth and life sciences, physical and space sciences are taught least of all, and when taught, it is more often by teachers with minimal qualifications, particularly in hard-to-staff urban schools (Blank 2003; Murphy, DeArmond, M., & Guin 2003; National Council on Teacher Quality 2004). Teachers' perceptions of their own preparedness for teaching different science disciplines mirror these findings (Fulp 2002; Seastrom et al. 2002).

How a teacher presents curricular materials is also important. The structure of the ARIES curriculum permits both experienced and novice teachers the latitude to use the materials in a manner consistent with their preferred style of teaching, without significantly diminishing the discovery-based explorations. As noted earlier, ARIES embeds the processes of science in the student science journal to go hand in hand with the students' conceptual growth. We designed the sequence of explorations in any ARIES module to provide a framework for that conceptual growth. Teachers are able to build on that framework and at the same time bring their own special strengths and interests to the classroom experiences of their students.

The blueprint for changing science education outlined in the National Science Education Standards (National Research Council 1996) provides both a destination and a map to reach that destination for those working to improve science education. Much of that map calls for changing emphases from many of the current practices to "exemplary" models of teaching and learning that encompass to a greater degree the investigatory nature of science. The ARIES curriculum mirrors in most every respect these changing emphases called for in the teaching, professional development, assessment, and content and inquiry standards. There should be less emphasis on easily measured, discrete science knowledge assessed by finding out what students do not know (i.e., have not successfully memorized), and more emphasis on assessing whether students have rich, well-structured knowledge and can apply science reasoning by determining what they understand. In ARIES, we envision learning as building new models for understanding the natural world. The sequence of explorations in the student science journals reflects the shared sense of CfA and SED scientists and science educators about the overall learning objective of having students understand the nature of science through emphasis on only one topic (or at most two particular topics) in a module. The student science journals become a daily record of that learning. Students are asked to make predictions, observations, and records of natural phenomena; through these steps, they build new models for understanding the world. This new understanding is encapsulated in the final part of each exploration—an embedded assessment component—in which the students write out or draw what they have come to know. In ARIES, greater emphasis is placed on conceptual understanding, inquiry, history and nature of science, extended investigations, and the use of evidence from nature to draw inferences about the world. Few subjects lend themselves so well to all these elements of good science as do physical and space science.

For the elementary-grade students, some concepts that we assessed seem decidedly less susceptible to a constructivist approach than others. In particular, there were two concepts that the students using the investigatory ARIES explorations did not understand as well as other concepts: using outdoor shadows to tell time, and describing what makes the number of daylight hours change from summer to winter for most locations on Earth. We suggest that transferring (or integrating) concrete observations of natural phenomena into subtle and abstract models of nature's behavior is difficult and in these two instances may exceed the cognitive ability of many Grades 3–6 students. However, the significant difference in learning by the ARIES students when compared with the learning by the control students, especially as it relates to the concepts that students find, a priori, to be the most difficult, underscores the effectiveness of the ARIES curriculum.

An Abbreviated Listing of some of the SED's Curricula, Publications, and Media Programs:

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Appendix

Click here to access the ARIES sampler test in PDF.

URL: http://aer.noao.edu/auth/wardappendix.pdf