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Abstract. The Turning Eyes to the Big Sky project offered schools in southwestern Montana a unique opportunity to strengthen science instruction. The project implemented, in a formal setting, a nationally established informal science curriculum on light and optics, the Hands-on Optics *Terrific Telescopes* curriculum. *Terrific Telescopes* was implemented in eight middle-school classrooms and reached 166 students during the 2010 to 2011 school year. As part of the project, we conducted a teacher workshop and assessed student learning outcomes and teachers' experiences with the curriculum. The goals of our assessments were to improve our understanding of how students learn key optics-related principles, provide evidence of the learning outcomes of *Terrific Telescopes*, and find out how teachers adapt the curriculum for use in formal settings. Our research established that students in every classroom learned optics concepts, uncovered student ideas about telescope optics, and identified ways to support and supplement the curriculum for use in classrooms. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.52.6.069001](https://doi.org/10.1117/1.OE.52.6.069001)]

Subject terms: geometric optics; optics education; telescope; middle school; student conceptions.

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1 Introduction

Twice in recent years, the National Research Council highlighted the prevalence of optics in our everyday lives and predicted the field to become even more critical in the next century.^{1,2} Optics is a rapidly developing industry with a growing need for qualified workers. To influence students to pursue careers in optics, their awareness of and interest in optics must be sparked well before they graduate from high school. SPIE—The International Society for Optical Engineering, has long recognized this need and invested in precollege education in light and optics. In 2001, SPIE and the Optical Society of America (OSA) held a series of workshops that culminated in a vision for optics education in the 21st century.³ Among the high-priority topics they identified for problem-solving were reaching a diverse group of learners, preparing grade K-12 educators to teach optics, and activating SPIE volunteers to help accomplish these goals. Turning Eyes to the Big Sky (TEBS) merged these key tasks in a project led by a SPIE undergraduate member (author R.H.) that provided training to eight middle-school teachers and assisted them in implementing the *Hands-on Optics* (HOO) *Terrific Telescopes* curriculum in their classrooms.⁴ While other projects have reported on similar teacher preparation or curriculum implementation projects related to HOO, TEBS took the further step of measuring student outcomes and collecting teacher feedback after the curriculum was taught.^{5,6} The results of TEBS add to our understanding of how to effectively

teach optics, specifically basic geometric optics, to precollege students.

2 Learning Optics

Understanding the behavior of light is fundamental for learning optics but challenging for students. Previous research shows that students do not readily understand that light travels through space and variously describe it as filling space and remaining stationary, remaining as a glow around a source, comprising rays that fill space, or as rays spreading and illuminating space or surfaces.^{7,8} Students also express misunderstandings about the conditions that cause light to “bend” when passing through objects.^{8–10} In addition, students tend to interpret light rays concretely as physical entities emitted by a source, rather than as abstract, geometric representations used by scientists.^{8,11,12}

Prior studies have also shown that understanding how images are formed with lenses is difficult for students. When asked to reason about a converging lens task such as where a light bulb shines through a positive lens and appears as an image on a screen, many students did not employ light rays in a way that could accurately explain how the lens formed the image.¹³ Students expressed difficulty understanding the relationship of the components in the task (bulb, lens, and screen).¹¹ When asked what would happen if the lens was removed, students often incorrectly predicted that removing the lens would sharpen the image or that an image would still form on the screen.^{14,15} Many made erroneous predictions

about what would happen if the screen was moved away from or toward the lens, for instance, that the image would change size but remain sharp or that the image would become fuzzy but remain visible.^{8–11}

The research has focused on students in eighth-grade through university, when geometric optics is usually taught, but similar challenges and ideas are found among individuals from elementary school through adulthood.^{10,16} At any grade level, instructional approaches that allow students to reason about phenomena they experience firsthand can help them develop deep understanding of difficult concepts.^{17,18} The telescope provides an experiential way for students to learn key concepts in optics¹⁹ and may remove yet another conceptual difficulty that students encounter.¹⁹ Instruction on light is often coupled with instruction on how the eye receives light from objects, a concept difficult for students to understand.^{7,12} Students are better able to interpret the propagation of light when they consider it independently of sight.²⁰ While extending one's vision is the purpose of using a telescope, it is possible to investigate the interaction of the telescope with light without tackling how the eye sees.

3 TEBS Project

The motivation for the TEBS project was to strengthen science instruction on light and optics in late elementary and middle-school grades. Specifically, its goals were to train teachers to teach light and optics, involve students in light and optics instruction, integrate science-related technology into classrooms, place telescopes in the hands of hundreds of students, and inspire students to pursue science-related careers. TEBS pursued these goals by implementing a nationally-established informal science curriculum, HOO's *Terrific Telescopes*, in formal classrooms during the 2010 to 2011 school year. The project collected data to measure teacher and student responses to the curriculum and learning from the project.

3.1 Instruction and Materials

The *Terrific Telescopes* curriculum comprised the core of TEBS instruction. An educational collaborative of SPIE, OSA, and NOAO⁴ developed *Terrific Telescopes* to teach the optics of telescopes.^{4–6} It was originally designed for use in science centers around the world. It has been used in a range of informal and formal education settings, training 178 teachers and reaching upward of 30,000 people.²¹ TEBS

moved *Terrific Telescopes* into the classroom and provided resources for teachers to implement the curriculum.

Terrific Telescopes taught the basic properties of positive lenses, which focus rays of light to create images. The curriculum engaged students in approximately 2 to 3 weeks (in the classroom) of activities ranging from single lenses to two-lens telescopes. The curriculum guided students through explorations of refracting light rays in acrylic blocks and convex lenses, estimating lens focal length using distant objects, using a lens as a simple magnifier, and building a refracting telescope. The curriculum culminated in using student-built refractive telescopes to investigate resolution observed when viewing distant eye charts, a project designed to enable students to apply and extend their knowledge of lenses.⁶ Figure 1 shows two photographs of middle-school students engaged in this curriculum and one photograph of a teacher participating in a teacher-training workshop (described later).

Funding from a number of organizations allowed TEBS to provide each participating classroom the full set of materials necessary to teach *Terrific Telescopes* and more. A SPIE Education Outreach grant provided each classroom a *Terrific Telescopes* toolkit that included five pairs of equi-convex lenses (7.5- and 20-cm positive focal lengths), five simple refracting telescope kits, an acrylic block, a laser, and other materials. SPIE provided 300 additional simple refracting telescope kits for the project, resulting in approximately one telescope kit per student in each classroom, and provided funding that allowed TEBS to double the other materials for each classroom. Edelman Financial Services provided 75 Galileoscopes (50-mm diameter objective refracting telescope kits), which were distributed five per classroom.¹⁹ A number of organizations donated astronomy and science handouts and posters to classrooms.

TEBS supplemented the *Terrific Telescopes* implementation with two additional events. First, author R.H., a NASA Science Public Outreach Team (SPOT) member, gave SPOT's *Eye on the Big Sky* presentation to each classroom prior to the pre test and implementation of *Terrific Telescopes*. The presentation covered basic astronomy and current NASA missions in our solar system. The goal of the presentation was to introduce students to telescopes and excite them about science. Second, all participating students, teachers, and their families were invited to a free end-of-year Star Party during the university's annual Astronomy Day (held after the post-test for all classrooms except one).

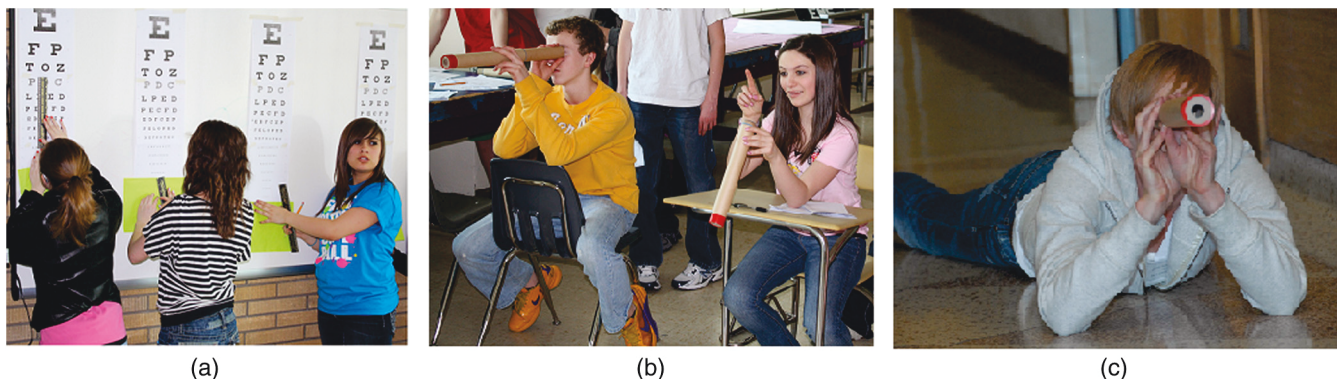


Fig. 1 Middle-school students (a, b) investigate refracting telescopes as part of the *Terrific Telescopes* curriculum. A teacher (c) uses a refracting telescope during the teacher workshop.

The Southwest Montana Astronomical Society planned to set up telescopes for night viewing, however, that was unfortunately cancelled due to overcast skies.

3.2 Participants

The overall TEBS project involved 15 teachers and approximately 409 students in fourth- through ninth-grade classrooms in southwestern Montana. Because the *Terrific Telescopes* curriculum has been found most appropriate for middle-school students,²² a finding corroborated by our own experience, we focused our analysis on the sixth through eighth grade classrooms participating in TEBS (eight teachers and 166 students in seven public schools). Table 1 describes the student populations of the participating middle schools and the communities in which they were located. Schools in our analysis varied in size from 38 to 639 students in grades seven through eight and included two schools serving Kindergarten through sixth grades. Student populations were predominately White (91% to 100%) and a large percentage of students at every school qualified for free or reduced lunch (22% to 45%). Schools ranged from rural (town population 1396) to urban by Montana standards (town population 37,280). One of HOO's goals was to reach underserved students. While the majority of students in TEBS were not ethnic or racial minorities, many were underserved in terms of their rural locations and the lower household incomes that qualified them for free or reduced school lunches.

We recruited teachers within a two-hour drive of the university (to make SPOT visits feasible) by sending invitations through university and state contact lists for teachers of science and by contacting schools and teachers directly and via a press release. Table 2 describes the eight middle-school teachers who took part in TEBS (names are pseudonyms). Teachers ranged in teaching experience from 1 to 35 years and in education from a bachelor's degree in elementary education (grades K-8) to a doctorate in science education. They

taught sixth- through eighth-grade classrooms with enrollments of 13 to 29 students per classroom. The number of middle-school students participating in the *Terrific Telescopes* instruction totaled 166. Our analysis included the 156 students (94 female, 62 male) who returned consent forms and for whom we had both pre and post tests (94%).

3.3 Teacher Workshop

At the beginning of the 2010 to 2011 school year and before implementing the curriculum in their classrooms, participating teachers met at the university for a one-day workshop. Author R.H. led the workshop with the support of authors J.S., a professor of electrical engineering and physics and director of the Optical Technology Center, and M.L., a professor of science education. J.S. gave teachers an overview of the science of light and optics. The team facilitated the teachers, working in small groups, in completing the *Terrific Telescope* activities. M.L. led the teachers in discussion about using the activities in inquiry-based instruction. At the workshop, teachers received the *Terrific Telescopes* curriculum guide, all the materials, state teaching license renewal credits, and a project t-shirt.

3.4 Data Collection

3.4.1 Teachers

We collected multiple sets of data from teachers. First, we gathered teacher feedback on the workshop itself, including self-assessments of their knowledge of light and optics and their readiness to teach *Terrific Telescopes*. Second, we administered the draft student test on light and optics to teachers before and after the workshop. We compared teachers' pre and post test scores to measure their learning from the workshop and scored their tests using a similar approach to that described for students in the next section. We also gathered feedback from the teachers on the test itself and used it to revise the test (clarifying, adding, and re-ordering

Table 1 Demographics of participating schools.

School	A	B	C	D	E	F	G
Grades	7-8	K-6	6-8	7-8	K-6	7-8	7-8
Student enrollment	639	256	319	38	162	94	52
Free or reduced lunch (%)	45	30	41	43	N/A	34	22
American Indian or Alaskan Native (%)	5	<1	2	0	0	1	0
Asian American (%)	1	<1	<1	0	1	0	0
African American (%)	<1	0	0	6	1	0	0
Hispanic or Latino (%)	2	<1	3	0	0	2	0
Native Hawaiian or Pacific Islander (%)	<1	<1	<1	0	0	2	0
White, Non-Hispanic (%)	91	97	95	94	98	95	100
Town population	34,200	1650	7380	37,280	37,280	1396	37,280

Table 2 Demographics of participating teachers.

Teacher name	Thomas	Vaughn	Sanders	Rogers	Smith	Larson	Becker	Oliver
School	A	A	B	C	D	E	F	G
Grade taught	8	8	6	8	8	6	7	7
Students participating	29	25	17	21	13	21	18	22
Highest degree	BS	MS ^a	MS	MS ^a	BS ^a	BS	EdD ^a	MS ^a
Years teaching	1	25	19	2	4	30	35	8
Sex	M	M	F	F	F	F	M	F

^aHighest degree in science education, technology education, or a field of science.

questions) before they administered it to their students. Finally, teachers answered a survey after concluding the TEBS project, providing feedback on the *Terrific Telescopes* curriculum and their experience teaching the curriculum and giving recommendations for how to improve the experience for teachers and students.

3.4.2 Students

We assessed student attitudinal and learning outcomes by having teachers administer a test to students before and after they engaged in the instruction. We are not aware of a validated test for optics and telescopes, therefore, we developed our own test for the project.^{23,24} We used the same test for pre and post tests, thus allowing us to compare student scores before and after TEBS. The test asked two attitudinal questions. The first was “Do you like science?” which students answered on a five-point scale (1 = I do not like science at all, 2 = I kind of don’t like science, 3 = I don’t know whether I like science or not, 4 = I kind of like science, 5 = I like science very much). The second was “Have you ever thought about becoming a scientist?” to which students answered yes or no. The next set of questions investigated what students knew about light rays, asking them to identify what the lines coming off a drawing of the sun represented

and to illustrate how light from a flashlight would get to an apple. The following set queried their knowledge about telescopes including focus, focal length, and image detail. These three questions are included in Appendix A. The final question asked students to identify parts of a telescope in a drawing and prompted with the terms tube, simple magnifier, and objective lens.

We scored students’ pre and post tests using a coding scheme (Table 3). Two researchers developed specific criteria for each question based on the levels of understanding expressed in the answers, resulting in a score of 0 to 3 points for each question. They developed the coding scheme in an iterative manner which included applying it independently, checking agreement, and revising the scheme to reflect negotiations about codes. After multiple iterations, the two researchers independently coded, then compared their codes for approximately 14% of the tests including both pre and post tests randomly selected from each classroom. The inter-rater reliability level for each question was 0.90 or above (proportion agreement) (range = 0.90 to 1.00). Test status as a pre or post test and students’ identifying information were masked during scoring.

While coding the open-ended items on student tests, the researchers noticed several unexpected, recurring ideas in the explanations students gave for two questions about

Table 3 Sample coding scheme for pre/post test Question 10: “Which telescope will give a more detailed image of the bird? Please explain your answer.”

Points	Description of understanding	Example explanation
0	<i>None</i> : Circled either telescope but gave no explanation	“It just works this way”
1	<i>More Naïve</i> : Circled either telescope; did not discuss focal length; may have included inaccurate ideas about length of tube, distance from object, or image detail	Explained choosing Telescope B because: “It’s bigger/larger”
2	<i>Intermediate</i> : Circled Telescope B; incorporated one aspect of expert understanding but included inaccurate ideas; or had a correct but partial explanation	“The longer the telescope, the less focused it will be but more detailed”
3	<i>More Informed</i> : Circled Telescope B; reflected expert understanding, that a longer-focal-length telescope yields a larger or more detailed (i.e., magnified) image; included no inaccurate ideas	“Telescope B is longer so it has a greater focal length so you can see farther and more detail”

telescopes (Questions 9 and 10 in Appendix A). It is important to first note that the telescopes the students worked with in the *Terrific Telescopes* curriculum had two equi-convex lenses with positive focal lengths. For such lenses, center thickness is a meaningful variable because it is directly related to lens curvature, the strongest determinant of focal length. Therefore, we expected students to select “Telescope A” as the telescope with the longer focal length (Question 9) because it had a thicker objective lens. In their explanations, many students identified factors other than lens thickness (hence curvature) as determining focal length. As a second note, a lens with a longer focal length typically results in a telescope with a longer tube and higher magnification and, thus, provides a more detailed image from a geometric optics perspective (neglecting aberrations and such factors). Therefore, we expected students to select “Telescope B” as the telescope that would provide a more detailed image of the bird (Question 10) because it had a longer focal length or longer tube. Students sometimes identified factors other than tube or focal length as determining image detail. To investigate students’ ideas further, two researchers independently identified recurring inaccurate ideas in students’ explanations for Questions 9 and 10, then brought their lists together to compile a core set. Next, they divided all pre and post tests between them and independently coded students’ explanations for expression of the inaccurate ideas. An explanation was counted as an inaccurate idea only if the reason was explicitly stated. For example, “I circled Telescope A because the shorter the tube the longer the focal length” counted, but “I circled Telescope A because I think it has a longer focus” did not. The two researchers compiled and discussed their results, then identified the inaccurate ideas with the highest frequencies of occurrence.

4 Results

4.1 Teacher Outcomes

4.1.1 Workshop feedback

We surveyed teachers at the end of the one-day workshop to find out how effective it was. They indicated their level of agreement, on a six-point scale (1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = slightly agree, 5 = agree, 6 = strongly agree), to five statements about the workshop. The statements and means (M) and standard deviations (SD) of teachers’ responses are presented in Table 4. Overall, teachers were very satisfied with the workshop and agreed that it improved their understanding of light and optics and prepared them to teach these topics in their classrooms.

4.1.2 Learning from the workshop

We gave teachers the draft student test before and after the workshop to measure how their understanding of light and optics changed as a result of the workshop. A paired-samples *t* test (a statistical technique that compares two population means in the case where two samples are correlated—here, pre and postworkshop scores) showed that teachers’ postworkshop scores ($M = 8.9$, $SD = 1.36$) were significantly higher than their preworkshop scores ($M = 6.5$, $SD = 1.69$; $t(7) = 5.16$, $p = 0.001$). (The *t* test result is reported as *t* and degrees of freedom, with *p* representing the probability that the *t* value occurred by chance alone.

Table 4 Postworkshop feedback from middle-school teachers; $N = 8$.

Statement	M	SD
As a result of this workshop, I feel prepared to teach the <i>Terrific Telescopes</i> curriculum in my classroom	5.3	0.71
The instruction in the workshop was appropriate for the audience (teachers)	5.6	0.52
The instruction in the workshop was appropriate for the topic of light and optics	5.5	0.76
This workshop improved my basic knowledge about light and optics	5.6	0.52
Overall, I was satisfied with this workshop	5.8	0.46

Unless otherwise indicated, all tests reported in this paper required a *p* value of ≤ 0.05 to be considered statistically significant.) The effect size (a descriptive statistic for the magnitude of difference between two sets of related data, calculated as the difference between two means divided by the standard deviation of the data) was large (Cohen’s $d = 1.82$).²⁵ These results indicate that teachers left the workshop knowing much more about light and optics than when they arrived. However, the average postworkshop score was only 68% of the total 13 points possible, with teachers’ scores ranging from 7 to 11 points.

4.1.3 Feedback on curriculum after implementation

After they completed the TEBS project, we asked teachers whether they would consider teaching the *Terrific Telescopes* curriculum again in their classroom. They responded on a scale of 1 to 10, where 1 = “strongly no” and 10 = “strongly yes.” Seven of the eight teachers indicated they would teach it again, however, one indicated s/he would not and explained that the curriculum guide was not clear (for all teachers, $M = 8.6$, $SD = 1.93$). We also asked teachers to indicate, on the scale of 1 to 10, how satisfied they were with the TEBS project. Overall, teachers were very satisfied ($M = 9.0$, $SD = 1.41$), but the same teacher was the least satisfied and explained s/he had hoped to gain a deeper understanding of optics in the project.

We asked teachers how they modified the *Terrific Telescopes* curriculum in their classrooms. Some teachers described implementing the curriculum as it was, while others described modifying the materials. Two teachers used clay to affix lenses to a meter stick to help their students determine focal length. Two substituted candles in activities involving light because it improved the visibility of the images. In addition, instead of using an eye chart to measure resolution of the telescope, which her/his class found difficult to use, one teacher used a chart with a single letter on it and compared the distance at which it came into focus with the naked eye versus the telescope.

We also asked teachers how they would recommend changing the *Terrific Telescopes* curriculum. Many teachers were pleased to have teacher background information, but identified the need for resource materials for students to aid

Table 5 Results for the question “Do you like science?” (1 = not at all, 5 = very much).

Classroom	Thomas	Vaughn	Sanders	Rogers	Smith	Larson	Becker	Oliver	All students
Pre test									
<i>M</i>	3.9	4.0	4.3	4.1	4.6	3.8	4.1	4.5	4.1
<i>SD</i>	0.80	0.89	0.78	0.72	0.51	0.92	0.86	0.61	0.81
Post test									
<i>M</i>	3.7	4.0	4.0	3.9	3.9	3.5	4.2	4.5	3.9
<i>SD</i>	1.11	1.08	0.97	0.97	0.95	1.12	0.81	0.51	0.99

them in making sense of light and optics concepts. They recommended including explanations and background information for students in multiple modes (e.g., powerpoints, videos, diagrams, demonstrations, readings, and vocabulary). Several teachers named concepts that needed more development in the curriculum: optics, the nature of light, and specifically, refraction. One teacher suggested combining the activities involving building a telescope to reduce repetition and two seventh-grade teachers advised dropping the resolution activity as it was too advanced. One classroom’s teacher and students all requested more clear directions and explanations for the activities, especially, for building the refracting telescope. One teacher raised concerns about the suitability of the questions on the pre/post test.

Teachers made comments that provided insight into issues of incorporating the *Terrific Telescopes* curriculum into a formal science classroom setting. Implementing *Terrific Telescopes* seemed unproblematic for the majority of teachers, however, several identified issues they needed to accommodate. One teacher added frequent formative assessments to check on student learning through the unit. Another had students use science notebooks, sketching and writing about concepts they were learning, and referring back to them as the unit progressed. One teacher attempted to connect the material to other topics the students were learning, especially the electromagnetic spectrum. In one school, astronomy was taught in eighth grade, light and optics in seventh, and the time available for teaching a given topic was limited which, together, made the curriculum challenging to implement. The limited time for teaching science in one sixth-grade classroom resulted in several days elapsing between activities, thus requiring a lot of review for students to be able to make connections between activities. Most teachers, however, said they and their students found this a great unit of study.

Teachers had recommendations about the TEBS project as well. Several teachers encouraged keeping or expanding the teacher workshop to prepare other teachers to teach the curriculum. Two advocated for continuing to provide teachers the necessary materials to teach the curriculum (e.g., lenses, lasers, acrylic blocks). All teachers affirmed they would welcome a SPOT presenter into their classroom again, saying that students love having guest speakers and learning applications of what they are studying.

4.2 Student Outcomes

4.2.1 Attitudes about science

One of TEBS’ goals was to positively affect students’ attitudes about science. The attitudinal questions implied mixed results for this goal. Table 5 presents the means and standard deviations for students’ responses to the first question about “liking” science. We used a mixed analysis of variance (ANOVA) to test differences in liking science from pre to post test and between classrooms. (The mixed ANOVA allows testing multiple variables in a repeated measures study design—here, change in individual students’ attitudes and differences in the change in students’ attitudes between classrooms; results are reported as F (degrees of freedom for variable 1, degrees of freedom for variable 2), p , and η^2 , with η^2 representing the percentage of variance accounted for by the instruction.) First, results indicated a statistically significant decrease in students’ reported liking of science from pre to post test, $F(1, 148) = 11.55$, $p = 0.001$, $\eta^2 = 0.072$. Figure 2 presents pre and post test frequencies of students’ responses to this question. On average, students became slightly less positive in how they felt about science. When we looked at how individual students changed, however (Fig. 3), we found that while some expressed a decreased affinity for science from pre to post test (24%), the majority expressed the same affinity (64%), and others expressed an increased affinity (12%). The second part of the mixed ANOVA assessed how liking science changed in different classrooms (see Fig. 4). Results indicated a statistically significant difference between classrooms, $F(7, 148) = 2.14$, $p = 0.042$, $\eta^2 = 0.092$. The change in students’ responses differed among classrooms taught by Thomas, Smith, Larson, and Oliver. Changes in liking science were small in every classroom and varied from increasing slightly, staying the same, to decreasing slightly. The largest decrease in liking science was expressed by students in Smith’s classroom, the teacher whose feedback about the project was highlighted above as being less positive than the other teachers.

Regarding whether they had thought about becoming scientists, we conducted a McNemar test (comparing within-student differences on a binary variable measured at two different times) to assess whether the number of students answering “yes” differed from pre to post test. Results indicated that at the post test, significantly more students thought

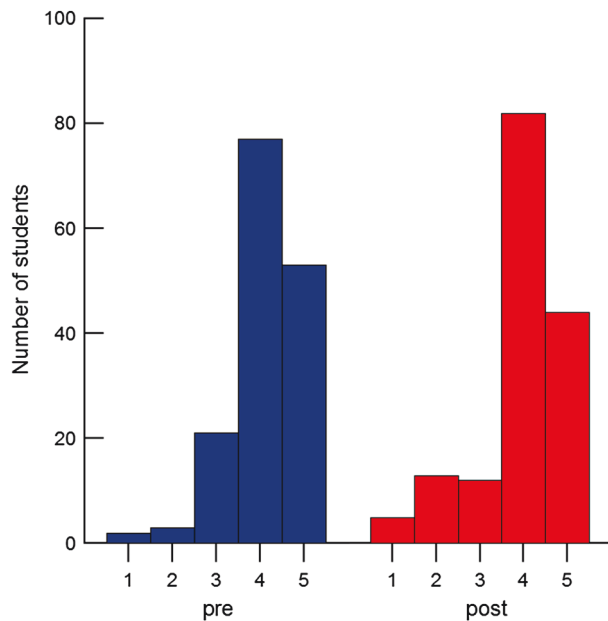


Fig. 2 Distribution of students' responses to the question "Do you like science" in pre versus post tests. Responses were given on a scale of 1 to 5 where 1 = "I do not like science at all" and 5 = "I like science very much."

about becoming scientists (46.1%) than did at the pre test (39.0%) ($p = 0.003$, $N = 154$). The effect size was moderate, Cohen's $d = 0.25$. Figure 5 presents frequencies of student responses to this question in pre versus post tests. We conducted a Chi-Square analysis to test whether the change in students' responses to this question differed by classroom. (Chi-Square tests for a relationship between two nominal

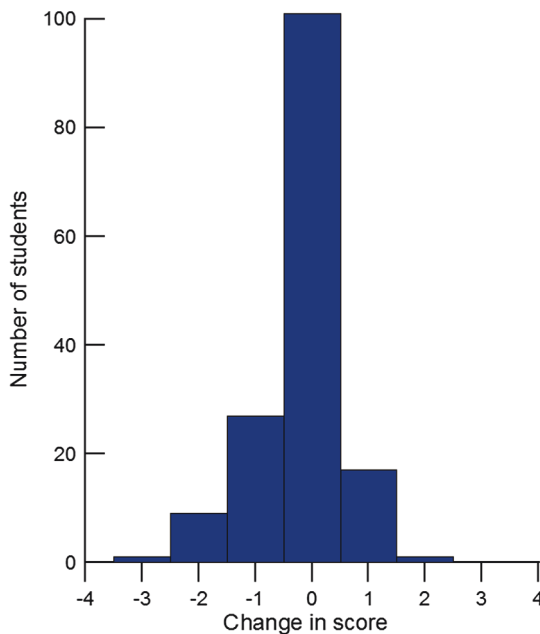


Fig. 3 Distribution of the degree to which individual students changed their responses to the question "Do you like science" from pre to post test, with negative numbers on the horizontal axis indicating students who decreased their "liking" of science, 0 indicating those who stayed the same, and positive numbers indicating students who increased their "liking" of science.

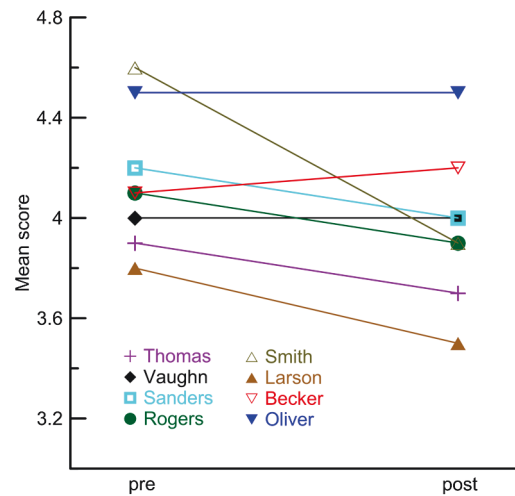


Fig. 4 Mean scores by classroom for student responses to the question "Do you like science" in pre test compared to post test.

variables—here, how students' responses changed [to "yes," to "no," or no change] and the classroom they were in; results are reported as a χ^2 value, the degrees of freedom, sample size, and p value.) The results indicated there was not a statistically significant difference on this question between classrooms ($\chi^2 = 10.76$, $df = 7$, $N = 153$, $p = 0.15$). In all classrooms, more students considered becoming scientists after TEBS.

4.2.2 Learning about light and optics

We were interested in how much students learned about light and optics in the project. The means, standard deviations, and effect sizes for students' pre and post test scores are presented in Table 6 and Figure 6. We conducted a mixed ANOVA to assess whether pre and post test scores were

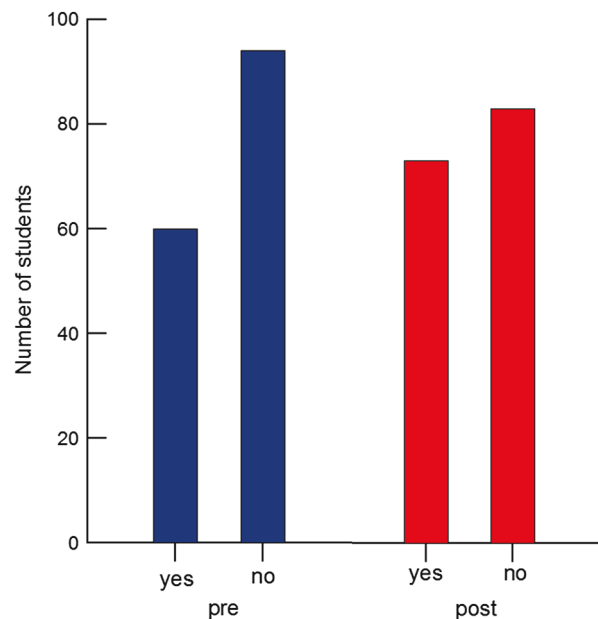


Fig. 5 Distribution of yes and no responses students gave to the question "Have you ever thought about becoming a scientist" in pre test compared to post test.

Table 6 Student learning outcomes.

Concept	Pre test		Post test		Effect size	Total score possible
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>d</i>	
Total score	9.6	2.72	11.5	2.83	0.61	18
Light rays	3.6	1.31	3.7	1.40	0.07	6
Focus and image	3.3	1.47	3.9	1.34	0.34	9
Parts of telescope	1.7	1.15	2.2	1.06	0.32	3

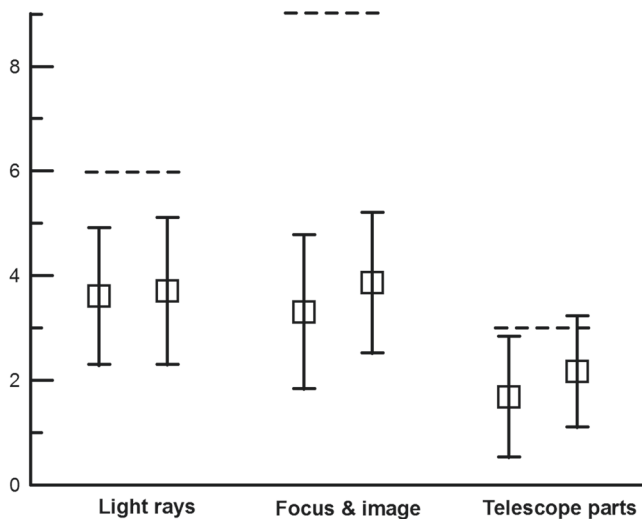


Fig. 6 Descriptive statistics for scores on questions about three sets of concepts in pre and post tests: light rays, focus and image, and parts of a telescope. In the graph, the box identifies the mean, the vertical line the sum of mean and standard deviation (SD), and the dashed line the maximum score for the concept. The distribution of scores for parts of a telescope were bimodal at 1 (more naïve), and 3 (more informed), resulting in the sum of the mean and SD exceeding the maximum score. This bimodal distribution indicates students either knew the names of telescope parts or did not.

different and whether changes in these scores differed by classroom. The first part of the mixed ANOVA results indicated a statistically significant increase in students' scores from pre to post test, $F(1, 148) = 24.82$, $p = 0.000$, $\eta^2 = 0.144$. Students experienced large overall learning gains as a result of participating in TEBS, though mean post test scores were just 64% of the total points possible. Students' scores on the sets of questions for focus and image and for parts of a telescope improved, yielding moderate effect sizes across classrooms. The mean post test score for the set of questions on focus and image (Questions 9 and 10 in Appendix A) was low, however, only 43% of the total possible score for this set. Mean scores for the set of questions about light rays increased but the effect size was negligible, implying there was not much change in understanding. The second part of the mixed ANOVA results indicated there was not a statistically significant difference between classrooms in how students' scores changed, $F(7, 148) = 0.88$, $p = 0.525$, $\eta^2 = 0.040$.

4.2.3 Student ideas about telescopes

Several unexpected and inaccurate ideas emerged in the explanations the students gave for their answers to the telescope focus and image questions (Questions 9 and 10 in Appendix A) in pre and post tests. These questions were written to assess students' understanding that: (1) the thickness of simple equi-convex positive lenses determines focal length (for these lenses, a thicker lens has higher curvature and therefore shorter focal length); (2) the focal length determines tube length (shorter focal length requires a shorter tube); and (3) focal length affects observable image detail (a longer focal length yields a higher magnification, which gives a more detailed view of a distant object). Students did not always identify these factors in explaining which telescope had the longer focal length or would give the more detailed image. Instead, several other explanations emerged (Table 7). The three most frequent inaccurate ideas students expressed were that the distance from the telescope to the object determines focal length, focus, or image detail; a shorter tube on the telescope produces a more clearly focused or detailed image; and a thicker or more highly curved lens produces a greater magnification or more detailed image. The explanation about distance was given in response to both Questions 9 and 10 (but more often for Question 10). The explanations about tube length and lens were given only for Question 10.

The instruction affected these inaccurate ideas in different ways. The idea about distance from the object determining focal length, focus, or image detail decreased substantially from pre to post test, but was still expressed frequently by students. Instruction appeared partially successful in shifting students' attention away from distance to focal length/lens thickness. The frequency of the explanation that a shorter tube length yields a sharper image did not change from pre to post test, indicating the instruction did not affect students' understanding of this. The idea about a thicker or more curved lens resulting in greater magnification or detail increased in frequency from pre to post test. This explanation was noteworthy because it skipped focal length and directly linked characteristics of the lens to image detail. To investigate this last idea further, we looked at its occurrence by classroom. The idea was expressed, on average, once per classroom on the pre test, but rose to an average of 6.3 times on the post test in three specific classrooms (Rogers, Thomas, and Vaughn). Students in these classrooms accounted for 79% of its occurrence on the post test, which

Table 7 Inaccurate ideas in students' explanations about telescopes in Questions 9 and 10.

Inaccurate idea	Example explanation	Pre test frequency	Post test frequency
Distance from object determines focal length, focus, or image detail	"[Telescope B gives a more detailed image] maybe because Telescope B is closer so you can see more detail close up" "[Telescope B has a longer focal length] because the bird (<i>sic</i>) is close so it is going to be bigger"	66	39
The shorter the tube, the better the focus or more detailed the image	"[Telescope A gives a more detailed image] because it is a shorter telescope" "[Telescope A gives a more detailed image] because it is shorter and you can get a background"	25	26
Larger thickness or curvature of the lens yields greater image detail or magnification	"[Telescope A gives a more detailed image] because it has a thicker lens" "The light is bent quicker through the thicker lens so the image would look much bigger and more detailed"	6	19

implies that instruction in these classrooms introduced or strengthened this idea.

5 Discussion and Conclusion

The TEBS project met its goals. We prepared eight middle-school teachers to teach *Terrific Telescopes*, increasing their knowledge of light and optics as a result, and providing them materials that will allow them to teach the curriculum in subsequent years. We involved more than 150 middle-school students in light and optics instruction and improved their understanding of these topics. The project successfully integrated science-related technology into eight middle-school classrooms, and placed telescopes in the hands of more than 150 students, including underrepresented students. Students improved their understanding of light and optics concepts in all classrooms. There were no differences in student learning between classrooms, indicating the *Terrific Telescopes* curriculum works in different school contexts, at all middle-school grade levels, and when taught by different teachers. More middle-school students thought about becoming scientists after their experience in TEBS.

As a group, while students' attitudes about becoming scientists increased after involvement in TEBS, their attitudes toward science decreased slightly. Two factors offer a more nuanced explanation about students' change in attitude toward science. First, the decrease in their liking of science was small and varied by classroom, indicating that variables other than the curriculum contributed to this outcome. In the classroom that saw the largest drop in students' liking of science, both teacher and students gave feedback that indicated they struggled with the science and the activities in the curriculum. Although their learning gains did not differ from other classrooms, these students apparently did not enjoy the experience as much as others. This implies more investment in teacher preparation could result in improving (or stabilizing) students' attitudes toward science.

The second factor is that although some students across classrooms gave science a lower ranking after TEBS, a majority of students gave it the same or a higher ranking. These results may reflect students gaining more information on which to base their feelings about science, resulting in a natural differentiation among students. Students in middle school may be actively discerning what subjects and careers "fit" and not all students will decide that science is for them. The TEBS project exposed students to a science, technology, engineering, and mathematics (STEM) area of which they

may have been previously unaware. The SPOT visit, in particular, which provided information about related careers, may have enabled students to envision themselves as future scientists, thus increasing their affirmative responses to the question about becoming a scientist. We recommend including information about STEM careers and introducing students, virtually or in-person, to young optics scientists or engineers as part of *Terrific Telescopes* or similar curricula. A reasonable goal, in the middle-school science classroom, is enlightening students about optics and optics-related careers. We recognize that exposure in middle school will not be sufficient to ensure interested and capable students will actually pursue careers in optics. Therefore, appropriate education opportunities need to be available through their high-school years as well.

The conclusions we can draw about TEBS' effects on students' attitudes are limited by the study design. Additional factors were, no doubt, operating in students' lives and control or comparison groups would be necessary to draw more definitive conclusions about how TEBS affected students' future academic or career intentions. A longitudinal design that follows students beyond high school would be required to see whether they realize those intentions.

The relatively low mean post test scores for both teachers and students, and the explanations students gave for the telescope questions, raise issues concerning the test questions and provide insights to guide future instruction. First, some test questions did not align completely with the curriculum. Specifically, our test included questions on light rays, which are instrumental in understanding formation of images by lenses, but light rays were not part of *Terrific Telescopes* instruction. Not surprisingly, students did not demonstrate an increased understanding of this topic after participating in the curriculum. While one course of action would be to drop questions about light rays from the test, we recommend a different course. Student learning may be better supported by including explicit instruction on light and optics as part of, or in concert with, the *Terrific Telescopes* curriculum. Specifically, it would be important to develop students' competency with ray tracing, a representation scientists use in light and optics, which may also improve students' understanding of telescope focus and image formation (discussed next). That notwithstanding, our light ray questions were not adequate to assess whether students understood rays as representations, rather than as physical entities, and could be revised to distinguish that understanding.

Second, the not-to-scale drawings in the test questions about telescope focus and image formation (Appendix A) may have elicited unexpected student ideas that we interpreted as inaccurate. Specifically, students explained that the distance between the bird and telescope would affect the sharpness of the image that formed. It is accurate to say that when an object is very close to or very far away from a telescope, it can be out of focus. We had not intended distance from the object to be a factor in the questions but, to many students, it was. Their experiences during instruction may have led to this idea. Some students were observed looking at objects situated closer than the focal length to the telescope's objective lens which meant they would have seen a magnified virtual image. It is possible that this "discovery" of the telescope acting as a simple magnifier led some students to a general conclusion that a more highly magnified (or detailed) image occurred when an object was located closer to the lens. This would be a case where a very relevant observation by the students led them to an incorrect general conclusion about the telescope. In the future, we would recommend that teachers receive training to help them recognize these different situations and to guide students to understand the difference between the simple magnifier case and the telescopic imaging case. Regarding the test, it would be informative to assess student understanding about how to modify telescope components to make a blurry image sharper and the effects of varying the distance between a given telescope and an object.

Third, and last, student ideas about the effects of tube length or lens curvature on image magnification or detail were sometimes the opposite of the actual phenomena. Students regularly, but inaccurately, stated that a shorter tube or thicker lens produced a more detailed image. These inaccurate ideas did not decrease as a result of instruction and, in the case of lens characteristics, increased. It could help reinforce the concept that telescope magnification is determined by the ratio of focal lengths for the objective and eye lenses, and increase the rigor of the curriculum, if students actually calculated magnification. If understood better, this could circumvent some of the incorrect conclusions that arise from the less direct arguments based on lens thickness or tube length. *Terrific Telescopes* provides two places where this may be addressed: (1) its introduction to simple magnifiers provides an opening to describe and calculate magnification as a ratio of image height to object height and (2) the first Refracting Telescope lesson provides an ideal place to introduce and calculate magnification as a ratio of lens focal lengths. Ray diagrams can support developing an understanding of magnification and focus. The concept of magnification could be introduced, for example, with a simple diagram of rays entering and exiting an afocal telescope. Students could be shown that this ray diagram creates two similar triangles whose lengths are equal to the focal lengths of the objective and eye lenses. By drawing several variations on this diagram, the students could see, directly, how telescope magnification depends on the combination of focal lengths. They could then calculate magnification, tying the concepts together. This approach may lead to a better understanding of optics and a better experience of optics instruction. Some middle-school students may not be developmentally ready for abstract ray diagrams. Yet, at any developmental level, students may benefit from

constructing an empirical understanding of the phenomenon. For example, students can make predictions about the effects of different lenses on tube length and image magnification, test their predictions, then derive "telescope principles" from their results. Test questions could be revised to more directly assess student understanding of focal length of individual lenses and pairs of lenses in telescopes, and the characteristics of their corresponding images.

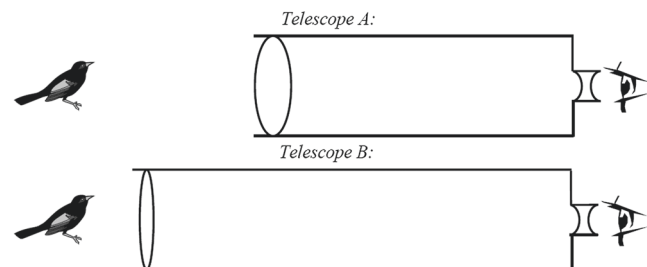
Through this process, we also gained insight into issues of implementing *Terrific Telescopes* in the formal classroom setting. The rigor of informal curricula may need to be increased for the formal classroom setting (in this case, namely mathematics). Classroom teachers are accountable for student learning and, moreover, of learning specific science and mathematics concepts and skills identified in K-12 standards. HOO curricula were developed to align with these standards, which may have allowed teachers to more readily incorporate *Terrific Telescopes*. While each teacher made changes in response to her/his own students or context, curriculum developers could include elements that would benefit all teachers. Specifically, identifying connections to other topics and infusing formative assessments that would allow teachers to monitor students' developing understanding and adjust instruction accordingly. Given teachers' need for evidence of student learning and the iterations it is taking our team to develop a valid pre/post test, it would be valuable if curriculum developers provided a test for teachers to measure student learning outcomes.

Terrific Telescopes provided an experiential way for middle-school students to learn concepts of light and optics in the classroom. It did not erase difficulties students have in understanding how lenses form images, but it did lead to improved understanding. The TEBS project results underlined the importance of assessing student understanding to determine whether instructional goals are being met, supporting teachers in learning the science themselves, and providing the resources they need to implement the curriculum.

Appendix A

Student pre/post test questions for telescope focus, focal length, and image formation:

8. Two telescopes are shown below. Please draw where the image of the bird would come into focus inside each telescope.



9. Which of the telescopes shown above has the longer focal length? Please circle your answer and explain why you think that is.

Telescope A/Telescope B

Please explain your answer here.

10. Which telescope shown above would give a more detailed image of the bird? Please circle your selection and explain why you think so.

Telescope A/Telescope B

Please explain your answer here.

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