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Project LITE Educational Materials and Their Effectiveness as Measured by the Light and Spectroscopy Concept Inventory

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Abstract

In this article, we present an overview of a suite of light and spectroscopy education materials developed as part of Project LITE (Light Inquiry Through Experiments). We also present an analysis of how introductory college astronomy students using these Project LITE materials performed on the Light and Spectroscopy Concept Inventory (LSCI) compared with students in courses employing other proven active engagement techniques and traditional lecture-based instruction.

1. INTRODUCTION

Though it is well documented that learning is vastly improved when students are moved from the role of passive listener to that of active participant in the learning process (Bonwell & Eisen 1991; Green 2003; Hake 1998; Prather et al. 2004; Sokoloff & Thornton 1997; Wandersee, Mintzes, & Novak 1994), the typical introductory astronomy course is still taught predominantly through lectures alone. Unlike physics, chemistry, or biology, in which common phenomena are easily testable in a laboratory setting, astronomical phenomena are often difficult to observe and even more difficult to reproduce in a classroom. Limited time and resources are major factors in preventing many astronomy classes from incorporating more interactive, hands-on activities and laboratory exercises.

Approaches such as peer instruction (Green 2003) and Lecture-Tutorials (Prather et al. 2004) have been developed and have made use of learner-centered in-class activities that are both inexpensive and easy to integrate into existing lecture format large-enrollment introductory astronomy courses. Computers are also playing an increasingly important role in science education (Zollman, Rebello, & Hogg 2002). Historically, the role of computers in astronomy education has been primarily focused on simulating astronomical observations and phenomena. Although there is undoubted benefit to having the means to visualize microscopic or astronomically distant phenomena, simulations and demonstrations are only pedagogically powerful if the students are actively involved through making predictions about what they are about to see, and engaging in discussions with their peers and instructor (Duncan 1999; Sokoloff & Thornton 1997).

Student difficulties with concepts related to light and spectroscopy are well known and documented (Bardar 2006; Brecher 1991; Comins 2001; Zeilik, Schau, & Mattern 1998). In response to the results of students' performance on questions relating to properties of electromagnetic radiation (Zeilik, Schau, & Mattern 1998), Michael Zeilik of the University of New Mexico stated, "I (MZ) have noted over 20 years of teaching that no topic seems more mysterious and confusing to novice astronomy students than that of light and spectra. Clearing up this bewilderment has no ready solution." The instructional materials developed as part of Project LITE (Light Inquiry Through Experiments) aim to make progress toward such a solution.

Project LITE is a National Science Foundation-funded software, curriculum, and materials development project spearheaded by the Boston University Science and Mathematics Education Center (NSF Grant No. DUE-0125992). Much of this project takes a unique approach to using the personal computer for science education by making use of its functional capacity to perform as an analysis tool and by making use of the photons from the monitor as a light source for interactive exploration of light and spectroscopic properties. All the software developed during the project can be found at http://lite.bu.edu.

The computer has long been the scientist's platform for data reduction and analysis and has recently become a popular tool for visualization and simulation in both astronomy and physics education, but the potential of the computer as a data source for experimentation is just beginning to be tapped. By using a personal computer as both a data source and an analysis tool, spectral exploration capabilities are extended to students at home as well as in the classroom. The educational goal of this project is to help students gain insight into the nature of light and spectra through individualized hands-on, eyes-on, and minds-on learning. Under the umbrella of Project LITE, a suite of hardware and software tools has been developed to enhance students' understanding of concepts related to light and spectroscopy. Components discussed in this article include interactive take-home lab activity kits and a spectral analysis software tool. Other components not discussed include a quantitative handheld binocular spectrometer (U.S. Patent No. 7,202,949); a student-designed electronic USB spectrophotometer; and LITE Vision, a suite of visual perception Flash applets.

During the 2005–2006 academic year, students in 34 course sections of introductory astronomy from 26 colleges and universities across the country participated in a field test of the Light and Spectroscopy Concept Inventory (LSCI) (Bardar 2006; Bardar et al. 2007; Bardar, 2008). The test was administered during the first week of the course to establish a baseline of content knowledge, and then readministered at the end of the course to determine the effectiveness of instruction in promoting conceptual gains. As discussed in Bardar (2008), the LSCI was found to have the sensitivity to (1) measure a statistically significant change in student understanding of topics related to light and spectroscopy due to the instruction provided in a semester-long introductory college astronomy course, and (2) differentiate between traditional instruction (primarily lecture) and active engagement treatments. In this article, we look specifically at the effectiveness of the use of Project LITE homelabs compared with other active engagement treatments and traditional lecture-based instruction.

The article is organized as follows. In Section 2, we discuss the components of Project LITE used by an introductory astronomy class at Boston University during the fall 2005 semester. In Section 3, we compare the effectiveness of Project LITE materials to that of other instructional techniques by content area, using the LSCI as a measure of success. Section 4 contains a discussion of our conclusions and offers suggestions for future work.

2. PROJECT LITE

2.1 Homelabs

The first component of the Project LITE suite of light and spectroscopy education tools is a set of six "homelab" activities. These inquiry-based quantitative experiments employ a novel optics kit comprising inexpensive existing commercial and industrial optical materials. These optical elements are used interactively with Java applets, enabling students to use the photons emitted by their computer screens to explore light-related phenomena such as diffraction, fluorescence, phosphorescence, and polarization. The materials kit was developed with a multitude of intended applications in a variety of disciplines, including physics, astronomy, chemistry, earth science, and even art and psychology. Each kit, pictured in Figure 1, contains the following 21 optical elements:

- 6 color filters (red, green, blue, yellow, cyan, and magenta)
- 2 neutral density filters
- 1 clear plastic sheet for demonstrating birefringence
- 3 polarizers
- 1 quarter-wave plate
- 1 transmission diffraction grating
- 1 translucent screen for image projection
- 2 flexible Mylar mirrors
- 2 convex lenses of different focal lengths
- 1 vinyl phosphor sheet
- 1 CD jewel case with one fluorescent side

Figure 1. Project LITE Light, Optics, Color, and Perception kit. Contents include optical elements for interactive experiments with light emitted from a computer monitor.

Homelab exercises include "guided discovery" activities, as well as more inquiry-based investigations. Experiments were designed for use by students in their homes or dormitory rooms with the goal of encouraging individualized hands-on, eyes-on, minds-on learning about light and optical phenomena. Light and optics are particularly suitable for at-home learning, because the required materials are interesting, inexpensive, and safe. Additionally, the use of homelabs can help to alleviate the major resource problem faced by many large introductory university science courses for nonmajors owing to the limited availability of laboratory space, equipment, and teaching assistants.

The following six homelab activities were part of the curriculum used by the Boston University AS102 (*The Astronomical Universe*) students who participated in the LSCI field test during the fall 2005 semester (section A0 as referenced in Bardar, 2008, and throughout the rest of this article).

1. **Diffraction:** Students become acquainted with the diffraction grating as a tool, construct a qualitative and quantitative understanding of the phenomenon of diffraction, and explore the relationship between color and wavelength.
2. **Geometrical Optics:** Students experimentally determine the focal length of a convex (converging) lens, explore how a refracting telescope works, make their own Keplerian telescope, and experimentally determine magnification.
3. **Fluorescence and Phosphorescence:** Students investigate the processes of fluorescence and phosphorescence and learn to recognize and identify fluorescence in astronomy.
4. **Introduction to the Spectrum Explorer:** Students identify the presence of specific chemical elements in spectra, explore Wien’s and Stefan-Boltzmann laws for blackbody radiation, develop a mental model connecting images and spectra with the underlying astrophysics, and cultivate pattern recognition skills.
5. **Color:** Students seek to understand the subjective nature of color, to understand how astronomical filters work, and to apply notions of color and filtering to naked-eye astronomical observations.
6. **Polarization:** Students identify polarization in the world around them and explore properties of

birefringence.

Each activity is five or six pages long and takes approximately 30–60 minutes to complete, depending on the individual student and activity. A standardized format was applied to these exercises, consisting of clearly stated objectives, a list of necessary equipment and materials, pertinent background information on the lab's content, and procedural guidelines. Background information includes relevant diagrams, drawings, images, equations, and definitions of new vocabulary. The included information also stresses the activity's connection to relevant astronomical applications, with the purpose of placing the activity in the context of the course. Interwoven throughout the procedures, students are asked to make predictions, record drawings, generate charts and graphs, and supply answers to conceptually challenging and probing questions as a way of providing gentle guidance while encouraging inquiry-based exploration of light-related phenomena and keeping the continuity and flow of the experiment.

Homelabs can either be assigned as a complete set over the span of an entire semester or used on an individual basis to suit specific course needs. During the LSCI field test period, students completed all six labs—one approximately every two weeks throughout the semester. An evaluation of students' conceptual gains by content area resulting from the implementation of these instructional materials is provided in Section 3.

2.2 Spectrum Explorer

Spectroscopy is arguably the most important tool used by astronomers to acquire information about the nature of the universe. However, it is one of the most conceptually challenging subjects for undergraduates. Among the most difficult concepts for students to master are Kirchhoff's laws, blackbody radiation, the Stefan-Boltzmann law, Wien's law, the nature and causes of emission and absorption lines, and the relation of spectra to underlying astrophysical processes. Students often seem baffled by the connection between a spectrum seen visually as a color band and the same spectrum plotted graphically as intensity versus wavelength or frequency. The Spectrum Explorer (SPEX) is a powerful Web-based tool developed to address these specific issues (Brecher et al. 2002; Weeks et al. 2003) by enabling users to simultaneously plot and compare multiple spectra, including blackbody spectra of any temperature, non–thermal power law spectra of a user-controllable spectral index, astronomical data files, and hand-drawn plots. SPEX is designed to be used by instructors in lecture presentations and by students learning at home or working in laboratory settings.

2.2.1 Content and Functionality

SPEX runs online as a Java applet or offline as a downloadable application that runs under Java Web Start for both PC and Mac. The installed application has support for features such as printing, saving, and exporting spectral data to the clipboard or file system. The opening screen of the SPEX interface is a blank spectral canvas. The software is intended to be the import, export, and manipulation tool for spectra that Photoshop and Microsoft Word are for images and words, respectively. Drop-down menus and a floating tool palette have been organized to parallel the formats of these widely used programs to make the interface familiar and easy to navigate. SPEX facilitates the creation, examination, comparison, and manipulation of spectra with blackbody, power law, Doppler shift, drawing, sonification, and zoom tools. It also allows for the simultaneous display of images and spectra taken from a data set embedded in the software, including stars, galaxies, nebulae, and quasi-stellar objects (QSOs). Spectra are displayed visually as a color band (either in color or grayscale) and graphically as a normalized or absolute-scale intensity-versus-wavelength (or frequency or energy) plot, a feature particularly valuable for students who struggle with the connection between the two representations. Figure 2 shows a SPEX screenshot depicting spectral analysis of the Crab Nebula.

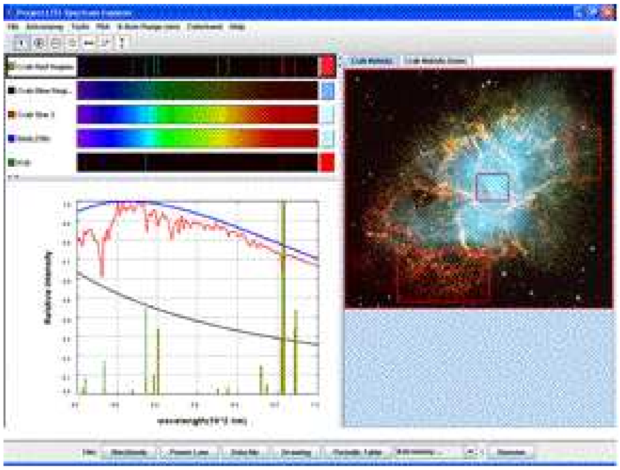

Figure 2. SPEX Screenshot of Spectra of Crab Nebula regions. Spectra are shown plotted for the red filamentary region, the central region of diffuse blue synchrotron emission, and the central G2V Main Sequence star. A 6250K blackbody and a laboratory hydrogen spectrum are also plotted for comparison.

2.2.2 Additional Features

Additional unique features of SPEX include an interactive H-R diagram, which enables students to simultaneously view stars on the H-R diagram alongside their graphical spectra (Figure 3), colorband spectra and a calculation of the overall color of the star (as represented by the color patch to the right of the colorband spectrum); a stellar evolution animation that traces the evolutionary path of a solar-mass star along the H-R diagram from time t = 10,000 years through $t = 1.3\text{x}10^{10}$ years; measuring tools for pinpointing the exact locations of spectral features; a customizable x-axis-range zoom tool for closer inspection of spectral features; a sonification tool for listening to spectra by mapping intensity to frequency and producing a MIDI (Musical Instrument Digital Interface) file; and a Doppler shift tool for determining kinematic properties of objects.

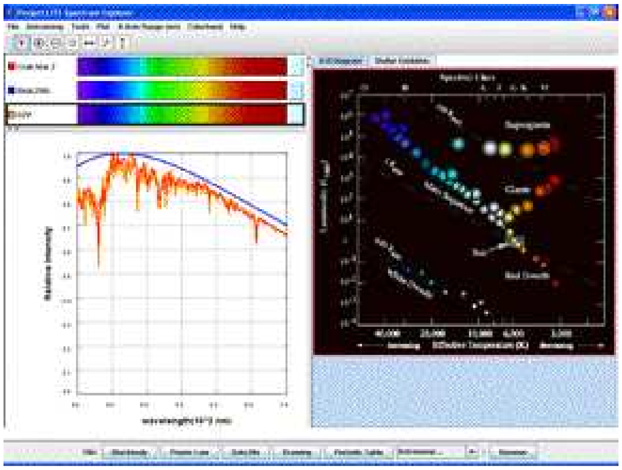

Figure 3. Classification of companion star to Crab Nebula's central pulsar. SPEX Interactive H-R diagram allows users to plot and compare stellar spectra of any spectral type.

In summary, the main features of SPEX 3.0, the most current version of SPEX, are:

- Plots blackbody spectra of any temperature
- Plots emission line spectra of any ionization state for any element on the periodic table
- Plots power law spectra with adjustable spectral indices
- Plots spectra of astronomical data files
- Freehand drawing tool
- Interactive H-R diagram
- Doppler shift tool
- Normalized or absolute flux scale
- Intensity versus wavelength, frequency, or energy
- Measuring tools
- Print/export capabilities
- Sonification tool for hearing spectra
- Adjustable x-axis range (zoom capability)
- National Virtual Observatory (NVO) search engine
- Fully explanatory user's guide

3. EFFECTIVENESS OF LITE MATERIALS

During the 2005–2006 nationwide field test of the LSCI, students using LITE instructional materials (section A0) exhibited one of the highest overall performance gains, with a postinstruction mean of 51.8% and an effect size of 1.31 (Bardar 2006, 2008). To evaluate the effectiveness of LITE materials in promoting conceptual learning gains in a meaningful context, we compared section A0's performance on the LSCI to that of students in traditional, primarily lecture-based courses and those in other active engagement classes (as defined in Bardar, 2008) employing techniques such as peer instruction or Lecture-Tutorials. Other than section A0, the only other course evaluated with the LSCI that was taught at Boston University was section B6, a primarily lecture-based course. All other sections participating in the

LSCI field test were from other colleges and universities.

This section looks at students' performance in each of the five content areas that comprise the concept domain of the LSCI: (1) the nature of the electromagnetic spectrum, including the interrelationships of wavelength, frequency, energy, and speed (NEM); (2) interpretation of Doppler shift as an indication of motion rather than color of an object (DOP); (3) the correlation between peak wavelength and temperature of a blackbody (WIE); (4) relationships between luminosity, temperature, and surface area of a blackbody (LTR); and (5) the connection between spectral features and underlying physical processes (PHY). The complete set of LSCI items can be found in Bardar et al. (2007). Table 1 shows a comparison of item difficulties (proportion of students answering the item correctly) for the entire preinstruction field test sample (N = 1883 for semesters 1 and 2 combined), and postinstruction means for the 21 traditional (T) primarily lecture-based sections (N = 1009), the 11 non-LITE active engagement (AE) course sections (sections B0, B4, B6, B7, B8, B9, C0, C4, C8, D1, and D5; N = 683), and students using LITE materials (section A0; N = 38). More detailed information about each individual course section can be found in Bardar (2008). Note that Section C5, an online course for in-service astronomy teachers, was omitted from the calculations shown in Table 1.

Table 1. Comparison of Students' Performance by Content Area

ITEM	CONTENT AREA	ALL (PRE)	T (POST)	AE (POST)	A0 (POST)
1	NEM	0.180	0.422	0.536	0.763
5	NEM	0.334	0.587	0.664	0.737
10	NEM	0.251	0.462	0.413	0.553
14	NEM	0.625	0.777	0.809	0.816
15	NEM	0.243	0.448	0.465	0.763
23	NEM	0.127	0.408	0.421	0.763
MEAN	**NEM**	**0.293**	**0.517**	**0.551**	**0.733**
2	PHY	0.110	0.165	0.216	0.132
7	PHY	0.214	0.296	0.364	0.421
8	PHY	0.152	0.299	0.382	0.447
11	PHY	0.181	0.277	0.430	0.395

13	PHY	0.297	0.444	0.487	0.789
17	PHY	0.192	0.236	0.247	0.316
21	PHY	0.278	0.290	0.176	0.474
22	PHY	0.121	0.209	0.277	0.211
MEAN	**PHY**	**0.193**	**0.277**	**0.322**	**0.398**
3	WIE	0.182	0.333	0.243	0.342
9	WIE	0.146	0.247	0.431	0.289
12	WIE	0.350	0.565	0.692	0.711
20	WIE	0.295	0.483	0.443	0.789
24	WIE	0.228	0.392	0.561	0.447
MEAN	**WIE**	**0.240**	**0.404**	**0.474**	**0.516**
4	DOP	0.211	0.666	0.547	0.763
18	DOP	0.279	0.372	0.360	0.447
19	DOP	0.192	0.336	0.315	0.526
MEAN	**DOP**	**0.227**	**0.458**	**0.407**	**0.579**
6	LTR	0.232	0.473	0.491	0.553
16	LTR	0.586	0.645	0.585	0.711
25	LTR	0.090	0.086	0.146	0.158
26	LTR	0.219	0.246	0.276	0.158
MEAN	**LTR**	**0.282**	**0.362**	**0.375**	**0.395**

3.1 Nature of the EM Spectrum (NEM)

Items 1, 5, 10, 14, 15, and 23 of the LSCI address the nature of the electromagnetic spectrum with respect to the relationships between the wavelength, frequency energy, and speed of light. Prior to instruction, the average fraction of students correctly answering items in this concept area was approximately 29%. Traditional instruction was able to help students improve on average to nearly 52%. Though this is a statistically significant gain, performance around 50% is unsatisfactory for questions that include a substantial amount of factual recall, such as the relative photon energies of the various colors of visible light (Item 5) and being able to identify radio waves as electromagnetic radiation (Items 1 and 23). Students in active engagement (AE) courses employing peer instruction and Lecture-Tutorials (sections B0, B4, B7, B8, B9, C0, C4, C8, D1, and D5) performed somewhat better on the postcourse assessment, with a mean score of approximately 55%. Students in section A0 who used the LITE materials, including the interactive light and optics homelab kits, exhibited the highest postinstruction scores in this content area, with an average of over 73% on items related to the nature of the EM spectrum.

3.2 Connection between Spectral Features and Physical Processes (PHY)

Students' understanding of the connection between spectral features and the underlying physics (Kirchhoff's laws) proved to be the weakest of the five categories evaluated. Prior to instruction, students scored an average of 19.3% on items in this classification (Items 2, 7, 8, 11, 13, 17, 21, and 22). After instruction, students in traditional courses improved to just 27.7%. Students exposed to active engagement treatments again performed somewhat better, with an average of 32.2% for peer instruction techniques and 39.8% for students who used Project LITE materials.

3.3 Correlation between Peak Wavelength and Temperature of a Blackbody (WIE)

Before instruction, students participating in the LSCI field test were able to answer questions regarding the correlation between the peak wavelength and temperature of a blackbody radiator (Wien's law) with a success rate of about 24%. As discussed in Bardar (2006), items in this concept area address a well-known phenomenological primitive (diSessa 1993) that "more is more." Items 9, 12, and 24 address the same concept, but each presents it from a slightly different perspective. Items 9 and 24 present graphical representations of nearly the same situation presented in Item 3, but Item 9 includes stellar spectra with absorption features. The spectra in Item 24 are featureless blackbody spectra, but the visual representation depicting the difference in relative heights of the curves reinforces students' intuition to choose the object with the tallest peak as the hottest object. Students had the most success with Item 12, in which the blackbody spectra have similar peak heights but different peak wavelengths. Overall, students in courses with lecture as the primary mode of instruction improved to an average of 40.4% on items in this content area. Students in the active engagement courses improved to 47.4%, and students in A0 to nearly 52%.

3.4 Interpretation of Doppler Shift (DOP)

Prior to instruction, approximately 23% of students on average were able to correctly answer items related to Doppler shift. After traditional instruction, students improved to just 46%, scoring highest (64%) on Item 4, which is essentially factual recall of the definition of Doppler shift. Significantly less success was exhibited on Items 18 and 19, which require students to apply their understanding of Doppler shift to line spectra by determining the relative speeds of objects based on their spectra. Non-LITE active engagement techniques resulted in slightly less improvement in students' abilities to apply their knowledge to hypothetical situations, with students scoring an average of 41% on Doppler-related items. Students in section A0 performed significantly better on these items, with an average success rate of 58%.

3.5 Relationships between Luminosity, Temperature, and Size of a Blackbody (LTR)

On items concerning the relationships between luminosity, temperature, and size of blackbodies (Items 6, 16, 25, and 26), the average preinstruction score was 28.2%. After instruction, students in traditional lecture-based courses scored an average of 36.2%, students in non-LITE active engagement courses scored an average of 37.5%, and students using LITE materials averaged 39.5%.

Figure 4 summarizes the results discussed in the preceding paragraphs in a plot of gain scores versus preinstruction scores by content area for each of the three categories of instructional technique: Active Engagement (AE) (Sections B0, B4, B7, B8, B9, C0, C4, C8, D1, and D5), LITE interventions (A0), and traditional lecture methods (T). The dotted lines indicate constant values of normalized gain, <g>, of 0.1, 0.25, and 0.5, where <g> is the ratio of actual gain to the maximum possible gain (100% – preinstruction mean). The value of <g> can be interpreted as the percentage of possible gain achieved. That is, <g> = 0.5 means that 50% of the maximum possible increase in score was attained. Traditional courses, indicated as diamonds on the plot, achieved normalized gain scores around or below 0.25 for all topic areas addressed by the LSCI, and below 0.10 in two areas, PHY and LTR. Section A0 achieved gains of 0.25 or better in all content areas except LTR. All other active engagement sections combined achieved normalized gains greater than 0.25 for only two of the five content areas, and between 0.1 and 0.25 for the other three. Gains greater than <g> = 0.5 were recorded only for A0 in the NEM category. These results strongly suggest that the implementation of the newly developed suite of spectroscopic learning tools was as effective as, or more effective than, other previously proven active engagement techniques—namely peer instruction and Lecture-Tutorials—in enhancing introductory college astronomy students' conceptual understanding of light and spectroscopy.

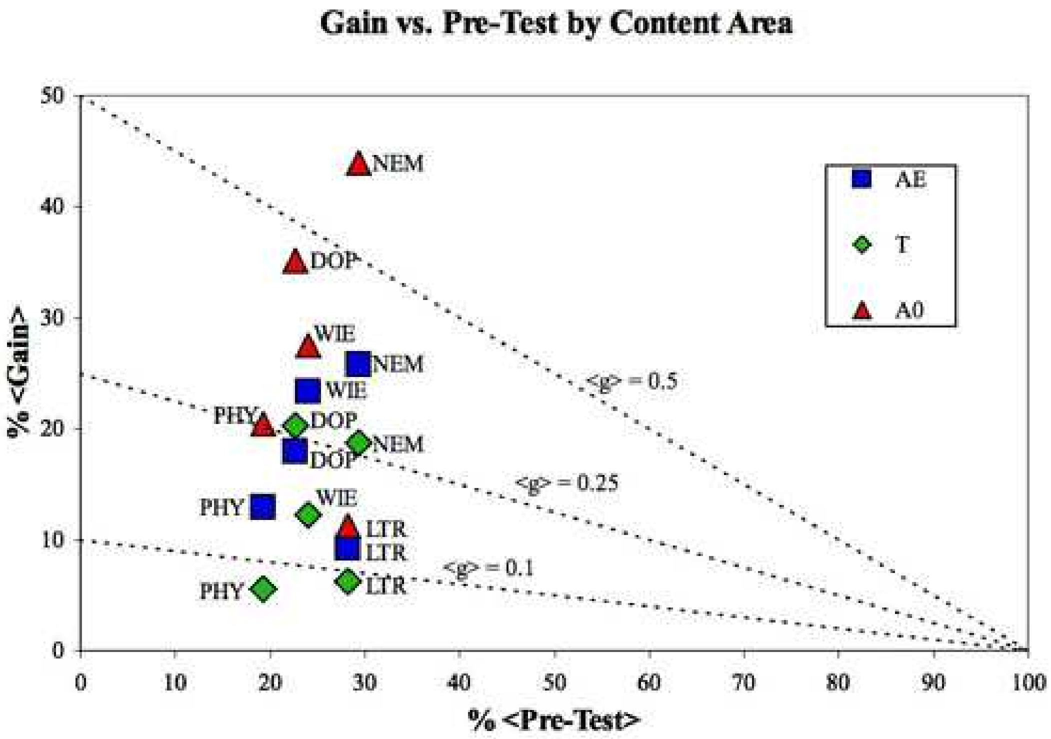

Figure 4. Comparison of the relative effectiveness of instructional interventions by content area. NEM = nature of the EM spectrum; DOP = interpretation of Doppler shift; WIE = correlation between peak wavelength and temperature of a blackbody; LTR = relationships between luminosity, temperature, and size of a blackbody; PHY = connection between spectral features and underlying physical processes. <g> indicates the normalized gain index, which is a ratio of the actual gain to the maximum possible gain. Blue squares represent active engagement (AE) course sections (other than A0); green diamonds represent traditional (T), primarily lecture-based courses; and red triangles represent section A0 (students using Project LITE materials).

4. SUMMARY AND CONCLUSIONS

This article has described the development and implementation of a suite of instructional materials designed to enhance students' understanding of concepts related to light and spectroscopy in the context of introductory college astronomy. The use of the personal computer to explore light and spectroscopic phenomena at a student's own pace and in the comfort of his or her own home or dormitory room is a major innovation of the project. The premise of individualized learning through homelabs provides an alternative approach to peer instruction (Green 2003; Mazur 1997) or Lecture-Tutorials (Prather et al. 2004) for incorporating learner-centered techniques into the large-enrollment introductory astronomy survey course. The Spectrum Explorer software enables students to simultaneously plot and compare multiple spectra in multiple representations to explore physical properties of objects and gain deeper understanding of the importance of spectroscopy to astronomy research. This software can also be used for lecture demonstrations and original research using NVO data.

The research objective of this study was to determine how the conceptual development of introductory college astronomy students using our spectroscopic learning tools (section A0) compared with that of students exposed to other instructional treatments, using performance on the LSCI as a gauge. Encouraged by the projected success of homelabs as exemplified by Chabay (1997), we hypothesized that the learner-centered nature of interactive take-home laboratory experiments would result in learning gains comparable with those achieved with other proven methods such as peer instruction and Lecture-Tutorials (Green 2003; Mazur 1997; Prather et al. 2004). Statistical analysis of LSCI results for students using Project LITE homelabs showed that the implementation of these materials and associated curricula was at least as effective as, or more effective than, in-class active engagement strategies such as peer instruction and Lecture-Tutorials, and more effective for all content areas tested by the LSCI. The take-home nature of these materials allows instructors to retain lecture as the primary mode of instruction while still implementing learner-centered activities as a major part of the course. The separate success of LITE and other active engagement treatments alludes to the possibility for even greater enhancement of students' conceptual understanding of light and spectra if the methods were to be combined.

The effectiveness of the LITE materials should be further investigated by implementing them in a course section not taught by one of the developers to guarantee that no inadvertent teaching bias is introduced that might influence the resulting measured learning gains. Additional data will be useful in strengthening the argument that the LSCI is a useful tool for the astronomy education community to demonstrate which instructional interventions are most successful in improving students' understanding of light-related concepts and in which content areas it is most difficult to effect conceptual change.

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