JOURNAL OF CHEMICAL EDUCATION

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Characterizing Instructional Practices in the Laboratory: The Laboratory Observation Protocol for Undergraduate STEM

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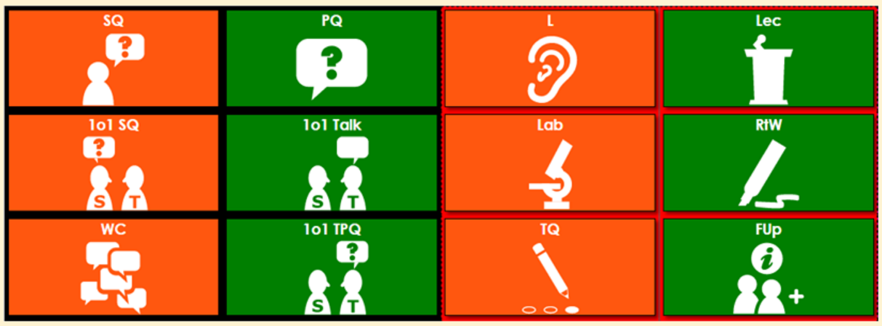
S Supporting Information



ABSTRACT: Chemistry laboratories play an essential role in the education of undergraduate Science, Technology, Engineering, and Mathematics (STEM) and non-STEM students. The extent of student learning in any educational environment depends largely on the effectiveness of the instructors. In chemistry laboratories at large universities, the instructors of record are typically graduate or undergraduate teaching assistants (TAs). Despite the importance of their role in the education of undergraduate students, TAs' instructional practices have been largely understudied outside specific reform efforts. In this study, we developed a segmented observation protocol, the Laboratory Observation Protocol for Undergraduate STEM (LOPUS), in order to characterize TAs' instructional styles in a General Chemistry laboratory curriculum. LOPUS captures both students' and TAs' behaviors every 2 min as well as initiators of verbal interactions and the nature of these verbal interactions (e.g., data analysis, explanation of concepts). Analyses of 19 videos collected from 15 TAs resulted in the identification of four instructional styles: the waiters, the busy bees, the observers, and the guides on-the-side. We found that students' behaviors were independent of these styles and limited to performing the laboratory activities, initiating conversation with TAs, and asking TAs questions. Interestingly, students rather than TAs were initiators of most verbal interactions, regardless of TAs' instructional styles. Finally, we found that the nature of TA–student verbal interactions was related to the nature of the laboratory activity (e.g., only following step-by-step instructions versus carrying out extensive data analysis). Implications of these findings for future research investigations and TA training are discussed.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Graduate Education/Research, Chemical Education Research, Laboratory Instruction, Professional Development, TA Training/Orientation*

FEATURE: Chemical Education Research

■ INTRODUCTION

To increase retention of Science, Technology, Engineering, and Mathematics (STEM) majors and enhance the scientific literacy of non-STEM majors, there has been a national call to transform postsecondary instructional practices in lower-level STEM courses.[1−4] These calls have resulted in numerous initiatives across institutions and STEM fields.[3,5−7] These initiatives have mostly been focused on instructional practices in the lecture hall, even though introductory STEM courses often also include a laboratory component. Indeed, students enrolled in an introductory chemistry course typically have a similar number of weekly contact hours with their lecture instructor as with their laboratory instructor. This lack of focus in transforming instructional practices in the laboratory may be connected to the limited empirical investigations conducted in these environments. The National Research Council report on the status of Discipline-Based Education Research (DBER) qualified the strength of conclusions drawn from laboratory studies in chemistry as limited.[5] This report called for more studies in laboratory settings, including explorations of the relationships between student learning outcomes and types of laboratory instruction. Although several studies have been published since

Received: January 23, 2016
Revised: March 13, 2016
Published: April 8, 2016

DOI: 10.1021/acs.jchemed.6b00062
J. Chem. Educ. 2016, 93, 1191−1203

the publication of this report, the majority focuses on student outcomes[8−16] or students' behaviors;[17−21] only few focus on graduate teaching assistants (TAs),[22−25] and none that we could find explore TAs' instructional practices.

The effectiveness of the instruction provided in the laboratory, as in many other educational settings, depends extensively on the instructor.[26−28] Undergraduate and graduate TAs have traditionally been the instructors of record for introductory STEM laboratory courses at large universities. Indeed, a national survey of research universities conducted in 2000 found that 70% of the life and physical sciences laboratories are taught by TAs.[29] A more recent survey of graduate students (N_{total} = 2218) conducted by the American Chemical Society (ACS) found that the main source of funding for graduate students is teaching assistantships.[30] Instruction in the chemistry laboratory has thus been investigated through analysis of TAs' and students' behaviors. Studies have explored the amount of time TAs' spent on performing laboratory tasks,[31−33] perceptions of laboratory instruction,[22,23,26,34,35] and the nature and content of student and TA interactions.[21,35−41] These studies have provided insights into dominant instructional behaviors enacted in a chemistry laboratory, such as the persistence of TAs' transmissive approaches to teaching,[36,37] the large percentage of time TAs spend manipulating equipment,[32] and the tendencies of TAs and students to talk about procedural and logistical concerns rather than underlying concepts.[21,31,32,35,38] However, most of these studies were conducted within the context of a laboratory curriculum reform effort and were either focused on one TA[21,38] or reported on TAs as aggregates.[31,35−37] Prior research, thus, does not report on instructional practices that take place in environments that are not undergoing reform, which are predominant in introductory college chemistry laboratory courses in the United States, and does not account for differences in how TAs implement a similar curriculum.[40] Documenting individual TA's instructional behaviors in the laboratory would help test hypotheses about the relationships between these behaviors and previously investigated aspects of laboratory instruction such as training, TAs' perceptions of their role, and student outcomes.[22,42] This study addresses these gaps in the literature by characterizing the different types of instruction enacted by 15 TAs in a typical (i.e., not reformed) laboratory component of a General Chemistry course.

■ APPROACHES TO THE STUDY OF INSTRUCTIONAL PRACTICES IN THE LABORATORY

Various methods have been used to characterize instructional practices in the laboratory: faculty and student surveys;[35] interviews with TAs, student, and/or faculty;[36,37,39] audio-recordings of a group of students working in the laboratory;[38] direct observations often accompanied by running records;[21,36,37] direct observations analyzed with internally[41] or empirically[31−33,40,42,43] developed observation protocols. Observations are the preferred choice for characterizing instructional practices as they can "document nuances and details of practice dynamics that are not documentable through other techniques." (p 30)[44] They also provide more objectivity than self-reports from instructors.[44] However, analyses of classroom observations provide more valid and reliable findings when conducted with structured observations protocols rather than unstructured ones (e.g., field notes) that focus on nonjudgmental aspects of teaching: "Observations are a strong method for documenting STEM teaching when they are conducted under well-defined protocols that capture what happens in a class session without the observer's subjective judgment regarding quality or the impact on student learning clouding the picture." (p 35)[44]

Three different types of structured observation protocols exist: holistic, segmented, and continuous.[44] Holistic protocols require observations of one laboratory session as a whole followed by ratings of a set of items based on the whole class observation. Examples of holistic protocols that have been implemented in STEM laboratory studies include the Reformed Teaching Observation Protocol (RTOP)[45] and the Teaching Assistant Inquiry Observation Protocol (TA-IOP).[43] Segmented protocols require observers to mark a set of behaviors as they appear within a specific time interval (e.g., 2 min). Examples of segmented protocols used in STEM laboratory studies include the Science Laboratory Interaction Categories−Student (SLIC),[32] the Category-Based Analysis of Videotapes (CBAV),[33] and the Modified-Revised Science Teacher Behavior Inventory (MR-STBI).[31] Continuous protocols collect information about behaviors continuously throughout the whole laboratory. An example of this type of protocol for the laboratory is the Real-Time Instructor Observation Tool (RIOT).[40]

Although these protocols have been empirically tested and provide meaningful data about certain aspects of instructional practices in the laboratory, they each have weaknesses. First, segmented protocols used in studies on instructional practices in the laboratory focus on previously agreed upon criteria for instructional quality rather than objectively describing behaviors.[46] Indeed, RTOP and TA-IOP require observers to rank TAs' and students' behaviors based on preferred practices observed in inquiry environments. As a result, interobserver reliability issues may arise and it may be difficult to communicate these results to TAs in an actionable manner.[47] Moreover, ratings resulting from these protocols may be reflective of the instructional materials in addition to the TAs themselves.[42,43] Since TAs are not often responsible for the design of the curriculum or the laboratory activity, the findings resulting from these protocols only partially represent TAs' instructional practices.[40] For example, neither RTOP nor TA-IOP may be appropriate for characterizing TAs' instructional practices in traditional laboratories as ratings will fit into a narrow, low range and miss variations in instructional practices outside the boundaries of inquiry instruction. In contrast, segmented protocols do not require observers to make judgments with respect to specific instructional quality criteria. However, segmented protocols that have been used in STEM laboratory studies are typically designed to focus either on students (SLIC, CBAV) or TAs (MR-STBI), not both simultaneously. As a result, they do not portray laboratory instruction as the interaction between students and instructors.[46,48] The only one continuous protocol implemented in the study of laboratory instruction, RIOT, captures student−TA verbal interactions, but no other student behaviors.[40] Finally, all three types of protocols do not capture the nature of students' and TAs' verbal interactions (e.g., discussions of concepts underlying the experiment, data analysis, or procedures to setup equipment), which may serve as indicators of the students' level of cognitive engagement[49] and focus of curriculum implementation.[21,38] This study attempts to address this set of weaknesses by developing a new protocol, the Laboratory Observation Protocol for Undergraduate STEM (LOPUS). LOPUS is a segmented protocol that characterizes (1) instructional behaviors without *a priori* criteria of quality, (2) students' and TA's behaviors, (3) the extent and initiator of verbal interactions between students and TA, and (4) the nature of the content being discussed during these verbal interactions.

DOI: 10.1021/acs.jchemed.6b00062
J. Chem. Educ. 2016, 93, 1191−1203

CONCEPTUAL FRAMEWORK

The design of LOPUS and the investigation reported here are grounded in Cohen and Ball's view on instructional capacity, i.e., "the capacity to produce worthwhile and substantial learning" (p 2):[48] instruction is a complex multifaceted phenomenon that involves interactions between instructors, students, and instructional materials (Figure 1). Cohen and Ball argue that reform efforts have typically focused on enhancing instructors' practices or improving the curriculum materials with the aim of promoting student learning, but not both at the same time. In their view, reforming instruction requires considering and studying the interactions between instructional materials, instructor, and students.

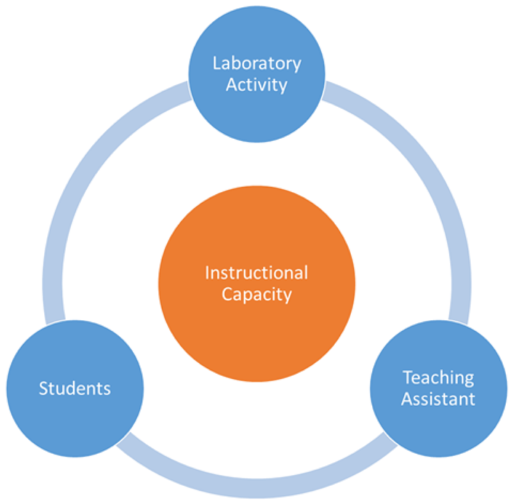


Figure 1. Instructional capacity depends on the interactions between teaching assistant, students, and the laboratory activity.

Research about instructors at the K−12 and postsecondary levels has demonstrated that instructors' prior experiences as students and teachers, the nature of their pedagogical content knowledge, and their beliefs about teaching impact their instructional and curricular choices as well as their ways of interacting with students.[48,50−56] Studies on TAs are aligned with these findings. In particular, studies have highlighted the relationships between TAs' past experiences as students, self-image, beliefs about teaching, and the nature of their pedagogical content knowledge with their enactment of the curriculum and interactions with students.[22,37,57−60] This prior work thus confirms the importance of studying how instructors interact with students and curriculum materials when characterizing an instructional environment.

Students also impact the instructional environment. In particular, their prior educational experiences, background in the content area, and expectations for the course impact their behaviors as well as their responses to instructors' teaching style and choices of instructional activities.[48,55,61−64] Studies on chemistry laboratory learning environments have also demonstrated these connections.[15,16,39]

Finally, the instructional material itself impacts how instructors and students behave. In completely expository laboratory experiments, the curriculum is limited to confirmation of predetermined outcomes in which the design and scientific methods used are already defined, limiting the extent to which instructors can act as facilitators or guides. Moreover, Hofstein and Lunetta who reviewed 20 years of research on laboratory instruction found that students were influenced by the laboratory activity itself as well as its written materials.[65] This finding was supported by Xu and Talanquer, who observed that the level of inquiry in chemistry laboratory activities influenced the nature and content of student talk.[21]

This study thus aims to capture (1) TAs' and students' behaviors and their relationships; (2) the extent and nature of their verbal interactions; and (3) the interactions between TAs' instructional styles, the laboratory activities, and the nature of these verbal interactions.

RESEARCH QUESTIONS

The goal of this study was to characterize the instructional practices TAs enact in traditional introductory chemistry laboratories. In particular, we aim to answer the following research questions:

1. How do TAs and students behave during traditional General Chemistry laboratories?
    a. How are students and TAs interacting in the laboratories?
    b. What are the instructional styles of TAs and the impact of these styles on students' behaviors?
2. What is the nature of TAs' and students' verbal interactions during traditional General Chemistry laboratories?
3. What are the relationships between TAs' instructional styles, the laboratory activities, and the nature of TAs' and students' verbal interactions?

METHODS

This observational study relied on the development of a new observation protocol. The description of the protocol and its development are provided below, followed by a description of the context of the study, the data collected, and the analytical approach. This study was approved by the University of Nebraska—Lincoln Institutional Review Board office (IRB approval # 20150215144 EX).

Development of the Laboratory Observation Protocol for Undergraduate STEM (LOPUS)

Our investigation required an observation protocol with the following characteristics: the instrument should capture (1) instructional behaviors without *a priori* assumptions about criteria for quality teaching, (2) the behaviors of TAs *and* students, (3) verbal interactions between TAs and students, and (4) the nature of the content being discussed during these verbal interactions. A literature review of laboratory-based observation protocols revealed that none fulfilled at least two of these criteria (see Introduction). However, a review of published observation protocols for the lecture environment revealed that the Classroom Observation Protocol for Undergraduate STEM (COPUS)[47] met the first two criteria and could thus be leveraged as a draft. COPUS is a segmented observation protocol in which instructors' and students' behaviors are recorded in 2 min intervals for the length of the lecture. Behaviors observed are objective and not judged against criteria of quality teaching (e.g., students are discussing a clicker question and the instructor is answering student questions versus the instructor is enacting inquiry-based teaching). This protocol has been demonstrated to provide highly reliable data with minimal training from observers.[47,66] Modifications to COPUS were necessary as it is focused on the lecture environment and therefore does not contain behaviors typically found in laboratory environments,

DOI: 10.1021/acs.jchemed.6b00062
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such as students waiting to manipulate an instrument or for reactions to occur. Moreover, COPUS does not capture the initiators (students or TA) of verbal interactions and the nature of these verbal interactions (e.g., discussions of concepts underlying the experiment, data analysis, or procedures to setup equipment). Steps taken to modify COPUS to fit the four criteria listed above are described next.

First, we conducted a literature review of studies on instructional practices in STEM laboratories to identify a comprehensive list of behaviors typically found in laboratory environments. After incorporating these behaviors into COPUS, we applied this new observation protocol to a few excerpts of laboratory videos that we had collected for another study. As a result, the new protocol contained new codes not present in COPUS (e.g., Lab, Students perform the lab activity; SI, Student initiates one-on-one interactions with the TA) and modified versions of COPUS codes (e.g., 1o1 SQ, Individual students or groups pose a question related to the lab activity to TA; 1o1 TPQ, TA poses a question to individual students or groups); some COPUS codes were also eliminated (e.g., CQ, Discuss clicker question). Finally, highly correlated codes (e.g., PQ, teaching assistant posing questions, and SQ, students answering questions) were reviewed, and only one code from each pair was kept in order to limit redundancy[66] and minimize the number of codes observers had to use.[44] Tables 1 and 2 present the list and abbreviated definition of TAs' and students' behavioral codes, respectively, that are included in the final version of LOPUS (see Supporting Information for full definitions). We classified both students and TAs' behavioral codes into three categories: typical instructional behaviors, interactive behaviors, and noninstructive behaviors.

Table 1. TA's Instructional Behaviors Coded in LOPUS

Type of Behavior	TA Code[a]	Abbreviated Definition
Typical instructional behaviors	**Lec**	Lecturing to the class
	RtW	Real-time writing on the board, doc cam, etc.
	FUp	Providing follow-up/feedback on activity
	D/V	Showing a demonstration or video
	M[b]	Monitoring class or individual groups
Interactive behaviors	**PQ**	Posing a lab-related question (nonrhetorical)
	1o1-Talk[b]	Talking to individual student or group of students one-on-one
	1o1-TPQ[b]	Posing a question to individual students or group of students
	VP[b]	Verbal monitoring and positive reinforcement
	TI[b]	Initiating one-on-one interaction with individual students or group of students
Noninstructive behaviors	Adm	Performing administrative tasks
	W	Waiting, not interacting, and generally unavailable to students
	O	Other

[a]Boldface indicates co-coded with nature of verbal interactions [b]Indicates code was either modified from COPUS or added.

Second, a new set of codes was created to characterize the nature of verbal interactions between TAs and students. The different types of verbal interactions were identified through the literature review of studies on STEM instructional practices in the laboratory and observations of excerpts of laboratory videos collected by the research team. Table 3 provides the list of codes along with their abbreviated definition (see Supporting Information for full definitions). Each of these codes was co-coded with the behavioral codes in boldface font in Tables 1 and 2. For example, if the TA posed a question to the whole class (PQ), a code from Table 3 was also used in order to characterize the nature of the question.

Table 2. Students' Behaviors Captured in LOPUS

Type of Behavior	Student Code[a]	Abbreviated Definition
Typical instructional behaviors	L	Listening to TA, video, or student presentations as a class
	Lab[b]	Performing the lab activity
	TQ	Taking a test or quiz
Interactive behaviors	**SQ**	Asking the TA a lab-related question with entire class listening
	1o1-SQ[b]	Individual student or a group of students asking the TA a lab-related question
	WC	Engaging in whole class discussion often facilitated by TA
	Prd	Making a prediction about the outcome of demo or experiment
	SP	Giving a presentation
	SI[b]	Initiating one-on-one interaction with the TA
Noninstructive behaviors	SL[b]	Leaving the lab for the day
	W	Waiting
	O	Other

[a]Boldface indicates co-coded with nature of verbal interactions. [b]Indicates code was either modified from COPUS or added.

Table 3. Nature of Verbal Interactions between TA and Students Coded in LOPUS

Nature of Verbal Interaction Code	Abbreviated Definition
Cpt	Underlying scientific principles
Ana	Data analysis and calculations
Exp	Experimental procedures, equipment, and laboratory techniques
Sft	Safety or cleanup procedures
Pvs	Previous laboratory activities, quizzes, or exams

Face validity of LOPUS was established through interviews with chemistry TAs ($N = 3$), chemistry faculty ($N = 3$), and STEM laboratory coordinators ($N = 4$). These interviewees confirmed that the list of LOPUS codes was comprehensive and they helped us refine definitions of some of the new/modified codes.

Inter-rater agreement (IRA) was assessed throughout the development process. IRA was calculated using Krippendorff's α[67] using the "irr" package in R (GNU General Public License). IRA calculations were based on the agreement between coders on the presence of the same behavior in the same 2 min interval. Pairs of raters, who independently coded the videos, achieved a median α of 0.82 (range 0.76–0.92) when coding with the final version of LOPUS. The videos used in this study were independently coded by three of the authors following establishment of IRA (J.B.V., A.K., D.X.).

Context of Study and Data Collected

The study took place at a university in the midwestern region of the United States classified by the Carnegie Foundation as high undergraduate, large four-year, primarily residential, very high research activity institution.[68] Fifteen General Chemistry TAs volunteered to be videotaped while teaching one or two different laboratory activities. Thirteen TAs were graduate students in the

DOI: 10.1021/acs.jchemed.6b00062
J. Chem. Educ. 2016, 93, 1191–1203

Table 4. TAs' Demographic Information and Number of Videos Collected from Each Group

TA Demographics		Number of TAs	Number of videos
Gender	Female	7	9
	Male	8	10
International status	Domestic	8	10
	International	7	9
Total		**15**	**19**

Department of Chemistry; two were undergraduate students. Parity in gender and domestic/international representation was achieved (Table 4). All participating TAs underwent identical laboratory training: during the week prior to the beginning of the semester, TAs were exposed to topics ranging from safety protocols, to proper behaviors with students; they also spent 1 day performing each laboratory activity covered during the semester. No emphasis on pedagogical approach was provided throughout the training. Throughout the semester, there were no weekly meetings to discuss upcoming laboratory activities.

Typical enrollment in this General Chemistry course is 24 students per TA per laboratory section. TAs taught two sections a week. All observed laboratories had similar structures: the period began with a short quiz on safety, followed by a prelaboratory lecture that included an overview of the activity, highlighting key procedures, and equations. For most of the observed laboratory activities, students then worked in small groups (2–4), with the option of collaborating with other student groups. Only two of the laboratory activities observed required students to work individually (aspirin synthesis and titration, Table 5). Laboratory periods were scheduled for 170 min, but students were allowed to leave upon completion of required tasks. This structure was typical for this institution and no pedagogical or curricular reforms were taking place when data was collected.

As Table 5 indicates, laboratory activities observed in this study span the first and second semester of a typical first-year General Chemistry curriculum. An analysis of the tasks and questions asked of students in each laboratory activity indicated that the nature of these activities covered a spectrum from conceptual (i.e., exploring concepts) to procedural (i.e., focus on following specific steps), to a mixture of procedural and analytical (i.e., manipulating and/or calculating quantities). Laboratory activities lasted on average 111 min (SD = 30 min).

Data Analysis

During this study, Qualtrics (Qualtrics, LLC) survey software was used to code the videos with LOPUS. LOPUS has since then been integrated into the Generalized Observation Reflection Platform (GORP), which is a web-based platform that facilitates data collection and analysis from user-created observation protocols.[69]

We used R and SPSS to derive descriptive statistics of (1) the proportion of behaviors, calculated as percentages of 2 min intervals in a video during which individual behaviors were observed, and (2) the proportion of codes describing the nature of verbal interactions, calculated as percentages of interaction-coded intervals co-coded with codes for nature of verbal interactions (Table 3). Hierarchical cluster analyses were also conducted in order to characterize commonalities in TAs' instructional styles and nature of verbal interactions.

■ FINDINGS

This study investigated instructional practices enacted in a traditional General Chemistry laboratory curriculum. In particular, TAs' and students' behaviors were investigated along with the extent and nature of TA–student verbal interactions and the relationships between the laboratory activities, TAs' instructional styles and the nature of theses verbal interactions. We organized the results of this investigation by research questions and subquestions.

Behaviors: Nature of TAs' and Students' Interactions

Descriptive statistics for students' and TAs' behaviors across all observed laboratories are provided in Figures 2 and 3, respectively.

Three students' behaviors were observed at high frequency across all observed laboratories: performing the laboratory activity (Lab, M = 84.0%, SD = 8.7%), asking questions to the TA on a one-on-one basis (1o1-SQ, M = 68.43%, SD = 17.2%), and initiating interactions with the TA (SI, M = 53.2%, SD = 14.9%). All other students' behaviors were either absent or, on average, accounted for less than 20% of the 2 min intervals. Overall, students spent the class completing the laboratory activity in their groups, engaged their TA in individual discussions, and rarely engaged with the TA or peers at the whole-class level.

Only one TA behavior was consistently observed at high frequency across all videos: talking one-on-one with a student or a group of students (1o1-Talk, M = 75.3%, SD = 12.5%). Although all other TAs' behaviors were observed across all videos, they occurred at low frequencies (less than 30% of the 2 min intervals on average) and varied extensively across videos (for example, monitoring the class, M, varied from 0% of the 2 min intervals in one of the VSPER lab videos to 75% in one of the butane lab videos).

Table 5. Characteristics of Laboratory Activities Observed

Nature of Laboratory Activity	Laboratory Topic	Short Description of Laboratory Activity	Number of Videos	Average Length of Activity in Minutes (SD)
Conceptual	VSEPR modeling	Draw Lewis structures and use plastic models to demonstrate geometries	4	97 (29)
	VSEPR isomers	Determine geometric/structural isomers of molecules	1	115
Procedural	Aspirin synthesis	Synthesize aspirin from salicylic acid and acetic anhydride	3	141 (25)
	Iodine titration	Determine NaClO in a sample of bleach	1	107
Procedural/Analytical	Aspirin titration	Determine purity of synthesized aspirin	1	176
	Butane	Identify molar mass through partial pressure	2	92 (5)
	Chemical equilibrium	Determine equilibrium constant through spectrometry	3	102 (15)
	Hess's law	Calculate enthalpies of acid–base reactions	2	119 (7)
	Ideal gas law	Use gas evolution to determine amount of given analyte	1	119
	Spectrometry	Determine amount of food dye in unknown sample using spectra of known dyes	1	49

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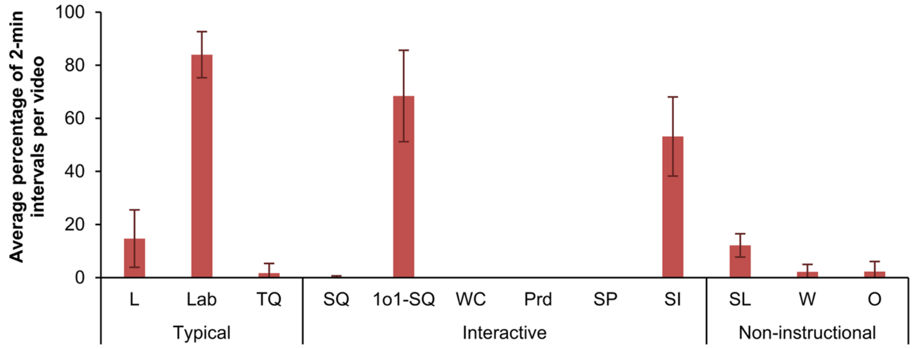

Figure 2. Average percentage of 2 min intervals per video containing each of the LOPUS codes for students. Error bars represent standard deviations. Definitions of abbreviated code are provided in Table 2.

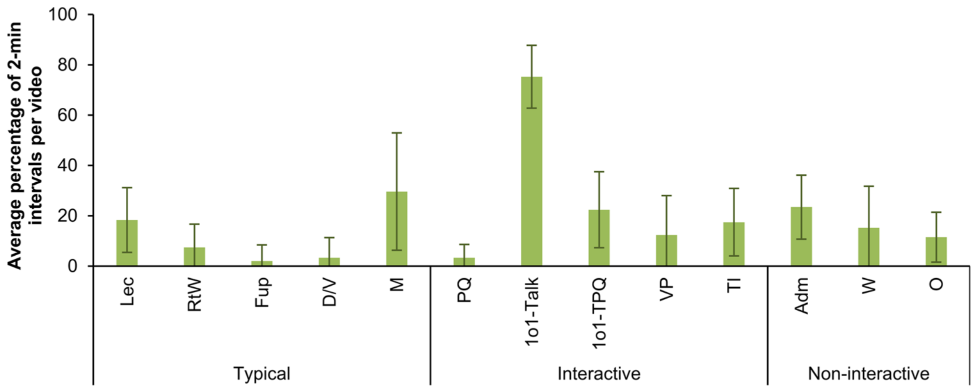

Figure 3. Average percentage of 2 min intervals per video containing each of the LOPUS codes for teaching assistants. Error bars represent standard deviations. Definitions of abbreviated code are provided in Table 1.

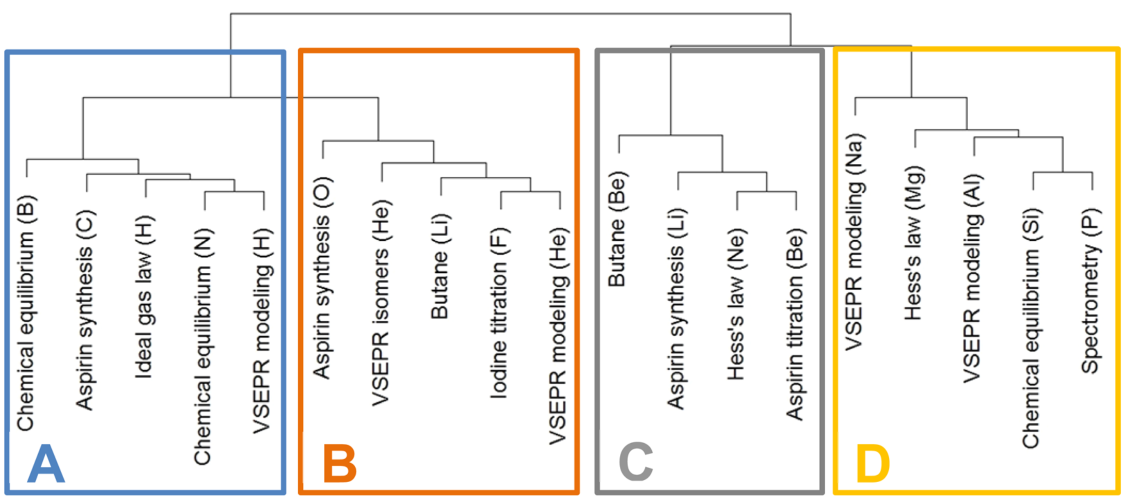

Figure 4. Dendrogram resulting from the hierarchical cluster analysis of students' and TAs' behaviors. Four TAs (Hydrogen, Helium, Lithium, and Beryllium) were observed teaching two different laboratory activities; all other TAs were observed teaching only one laboratory activity.

Overall, students were more likely to initiate one-on-one interactions with their TAs than TAs were with their students.

Behaviors: TAs' Instructional Styles

To examine the underlying patterns of TAs' and students' behaviors, we conducted a hierarchical cluster analysis in R using Ward's method. Ward's method is an agglomerative clustering method that merges pairs of clusters based on a given criterion, often the minimum variance between clusters.[70,71] With the use of percentages of occurrence of students' and TAs' behaviors (i.e., percentages of 2 min intervals in a video during which individual behaviors were observed) as input data, the analysis yielded four clusters (Figure 4).

To characterize the instructional style represented by each cluster, we analyzed both the frequency of students' and TAs' behaviors for each cluster (Figures 5 and 6, respectively) and differences in these frequencies across clusters using Kruskal–Wallis (K–W) rank-sum tests.[72] This nonparametric test was chosen due to the small number of videos in each cluster.[72] Post-hoc treatment of the data included the use of Dunn's multiple comparison test to determine significant differences between pairs of groups;[73] Holm–Bonferroni (H–B) corrections

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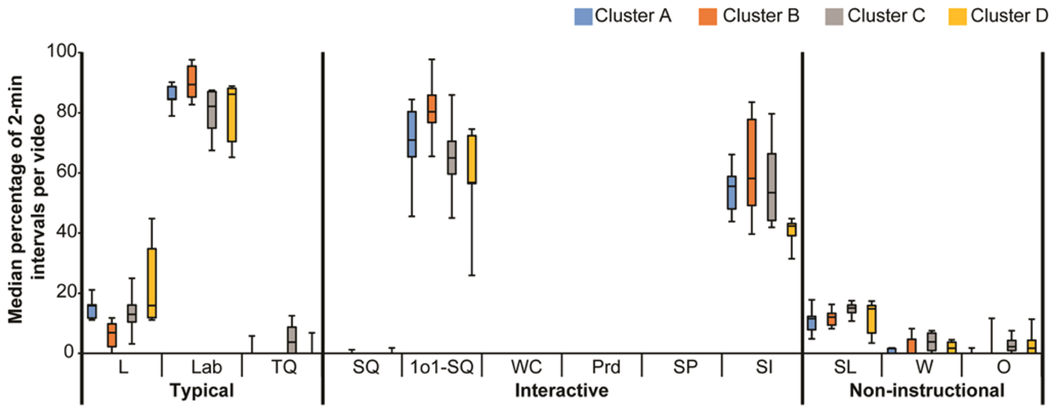

Figure 5. Median percentage of students' behaviors for each cluster. Definitions of abbreviated code are provided in Table 2.

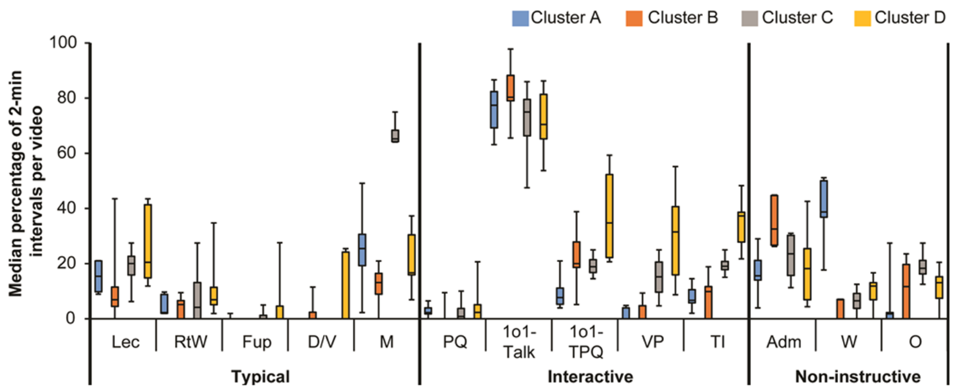

Figure 6. Median proportion of TAs' behaviors for each cluster. Definitions of abbreviated code are provided in Table 1.

were performed on the results of Dunn's test to minimize the occurrence of false positives from multiple comparisons.[74]

These analyses revealed that listening to the TA (L) was the only students' behavior with significant difference between clusters ($\chi^2(3) = 8.0272$, $p_{K-W} = 0.050$). Post-hoc tests indicated that this significant difference came from students in cluster D exhibiting this behavior significantly more than those in cluster B ($p_{H-B} = 0.025$). Overall, this behavior was infrequently observed with the highest median observed in cluster D at 15.9% of the 2 min intervals. Other students' behaviors had similar frequencies across all clusters: students' behaviors were thus not characteristic of any specific clusters.

Statistically significant differences between clusters with large effect sizes emerged when analyzing frequencies of TAs' behaviors (Figure 6). These differences led us to characterize each cluster as a different instructional style. These are described in the following paragraphs. Table 6 summarizes the characteristic behaviors of TAs in each cluster.

The Waiters. TAs wait for students to call on them. This instructional style corresponds to the TAs who were observed teaching in cluster A videos. Indeed, TAs in these videos exhibited a significantly higher frequency of waiting (W, $\chi^2(3) = 11.6964$, $p_{K-W} = 0.010$). Dunn's test revealed that cluster A TAs waited significantly more frequently than TAs in cluster B videos ($p_{H-B} = 0.004$). TA's waiting in cluster A was also observed more frequently than in clusters C and D videos (Figure 6). Moreover, TAs in cluster A videos engaged significantly less with students when compared to TAs in cluster D videos: Cluster A TAs initiated significantly less conversation with students (TI, $\chi^2(3) = 13.7947$, $p_{K-W} < 0.001$, $p_{H-B} = 0.005$), asked significantly less questions to individual students or groups of students

Table 6. Characteristics of Teaching Assistants' Instructional Practices in Each Cluster

Cluster Label	Instructional Style	Behaviors Significantly Different from Other Clusters (Median Percentage of 2 min Intervals)
A	The waiters	TAs spent more time waiting (38.7%)
		TAs asked fewer questions in one-on-one interactions (7.7%)
		TAs initiated fewer one-on-one interactions (6.7%)
		TAs provided fewer praise or verbal monitoring (0.0%)
B	The busy bees	TAs spent less time waiting (6.9%)
		TAs initiated fewer one-on-one interactions (9.8%)
		TAs provided fewer praise or verbal monitoring (0.0%)
C	The observers	TAs spent more time quietly monitoring their students (65.2%)
D	The guides-on-the-side	TAs asked more questions in one-on-one interactions (34.8%)
		TAs initiated more one-on-one interactions (37.3%)
		TAs provided more praise or verbal monitoring (31.5%)

(1o1-TPQ, $\chi^2(3) = 8.6290$, $p_{K-W} = 0.030$, $p_{H-B} = 0.010$), and provided significantly less verbal monitoring (VP, $\chi^2(3) = 12.1814$, $p_{K-W} = 0.010$, $p_{H-B} = 0.010$) when compared to TAs in cluster D videos. In general, cluster A TAs had the lowest frequency of enactment of these behaviors across all clusters.

The Busy Bees. TAs are constantly being called on by students or group of students to assist them with the laboratory activity. This instructional style corresponds to TAs observed teaching in cluster B videos. Indeed, these TAs initiated significantly less one-on-one conversation with students (TI, $\chi^2(3) = 13.7947$, $p_{K-W} < 0.001$, $p_{H-B} = 0.005$), and provided significantly less verbal monitoring ($\chi^2(3) = 12.1814$, $p_{K-W} = 0.05$ $p_{H-B} = 0.017$)

DOI: 10.1021/acs.jchemed.6b00062
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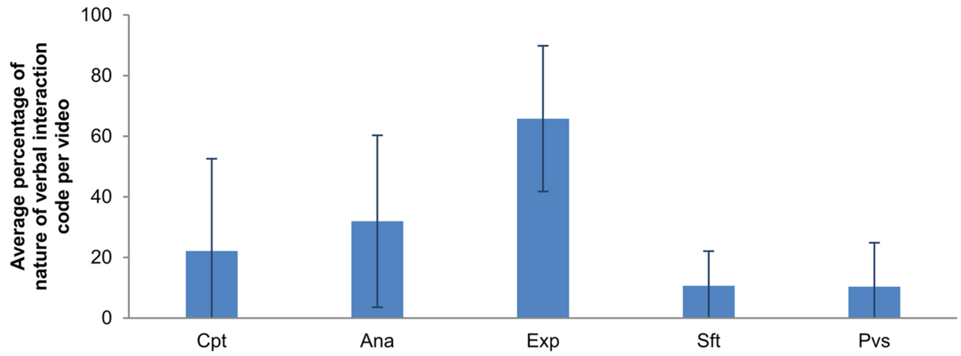

Figure 7. Nature of content discussed during interactions between TAs and students. Error bars represent standard deviations. Definitions of abbreviated code are provided in Table 3.

when compared to TAs in cluster D videos. As mentioned previously, they also waited significantly less than TAs in cluster A videos.

The Observers. TAs spend most of the laboratory session observing students performing the experiments. This instructional style was characteristic of TAs in cluster C videos. Indeed, monitoring (M) was the only behavior in cluster C that had a significantly different frequency when compared to the other clusters. Specifically, TAs in this cluster spent a significantly higher proportion of time monitoring students when compared to cluster B TAs ($\chi^2(3) = 10.7558$, $p_{K-W} = 0.010$, $p_{H-B} = 0.004$); the frequency of this behavior in cluster C was also 2.7-fold and 3.1-fold higher than in clusters A and D, respectively, but not statistically significant.

The Guides-on the-Side. TAs consistently praise, probe, and initiate conversations with students. This instructional style was characteristic of cluster D videos. As previously indicated, TAs in these videos spent significantly more time initiating one-on-one conversations with students (TI) and providing verbal monitoring and praises (VP) than TAs in clusters A and B; they also spent significantly more time asking questions to individual students or group of students (1o1-TPQ) than TAs in cluster A. Across the four clusters, cluster D TAs had the highest frequencies of using these three behaviors.

It is important to note that the median frequency for the TA behavior "talking to individual student or group one-on-one (1o1-Talk)" was above 70% in all clusters (Figure 3). Therefore, even the Waiters and the Observers spent a large amount of the laboratory session discussing with individual students or groups of students.

Nature of Verbal Interactions between Teaching Assistants and Students

The second research question of this study focused on the nature of the verbal interactions between TAs and students. Each TA–student verbal interaction (boldfaced codes in Tables 1 and 2) was co-coded with a code describing the nature of the verbal interactions (Table 3). It should be noted that each individual interaction may have been coded with more than one code from Table 3. For example, a TA teaching the Hess's law activity could be explaining to a group of students that some heat may still be lost to the atmosphere during the experiment (Cpt) despite using two coffee cups and a lid to insulate the system (Exp), and that they should take this factor into account when they make their final calculations of enthalpy (Ana).

Figure 7 shows the distribution of the nature of verbal interaction codes in all 19 videos, calculated from the percentage of nature of verbal interaction codes out of all TA–student verbal interactions coded in each video. Analysis of this figure shows that verbal interactions mostly focused on experimental procedures, the laboratory equipment, and/or laboratory techniques (Exp, $M = 65.8\%$, SD = 24.0%). Underlying scientific principles and data analysis/calculations were similarly discussed at lower frequencies (Cpt, $M = 22.1\%$, SD = 30.5%; Ana, $M = 31.9\%$, SD = 28.3%). Safety and previous materials were discussed minimally. Large variations were observed across videos for all five codes describing the nature of verbal interactions. We did not find any association between a specific type of verbal interaction, such as Lec or 1o1-Talk, and a specific code for nature of verbal interaction (see Supporting Information, Figures B and C).

Relationships between Nature of Verbal Interaction, Nature of Laboratory Activity, and TAs' Instructional Styles

The conceptual framework for this study pointed to the need to explore the interactions between instructors, students, and instructional materials when characterizing instructional practices in a specific learning environment. We thus explored the relationships between the nature of TA–student verbal interactions and the instructional materials as well as TA's instructional styles. To characterize these relationships, we first identified the underlying patterns in the nature of TA–student verbal interactions. We conducted a hierarchical cluster analysis across all videos using proportions of conceptual, analytical, and experimental verbal interactions. Three clusters emerged from this analysis (Figure 8). Kruskal–Wallis tests were conducted to identify significant characteristics of each cluster. These analyses revealed that the proportion of all three types of verbal interactions varied significantly between clusters (Cpt, $\chi^2(2) = 9.3920$, $p_{K-W} = 0.010$; Ana, $\chi^2(2) = 14.8680$, $p_{K-W} < 0.001$; Exp, $\chi^2(2) = 12.8350$, $p_{K-W} < 0.001$). Figure 9 illustrates these differences. Pairwise comparisons were conducted through Dunn's multiple comparison tests. These analyses revealed that cluster 1 had a significantly higher median for conceptual verbal interactions when compared to cluster 2 ($p_{H-B} = 0.004$) and cluster 3 ($p_{H-B} = 0.017$); cluster 2 had a significantly higher median for experimental verbal interactions when compared to clusters 1 ($p_{H-B} = 0.001$) and 2 ($p_{H-B} = 0.008$); finally, cluster 3 had a significantly higher median for analytical verbal interactions compared to clusters 1 ($p_{H-B} = 0.001$) and 2 ($p_{H-B} = 0.008$). Cluster 1 thus corresponds to conceptual verbal interactions, cluster 2 to experimental verbal interactions, and cluster 3 to analytical verbal interactions.

The relationships between the nature of TA–student verbal interactions and (1) the nature of laboratory activities as well as (2) TA's instructional styles are presented in Table 7. Analysis of

DOI: 10.1021/acs.jchemed.6b00062
J. Chem. Educ. 2016, 93, 1191–1203

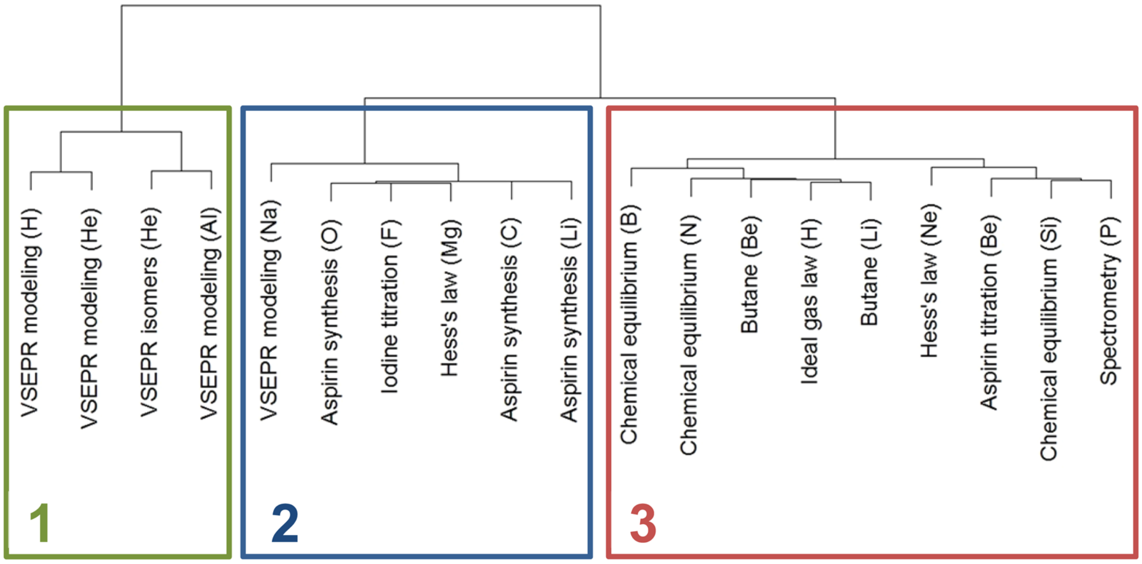

Figure 8. Dendrogram resulting from the hierarchical cluster analysis of the nature of verbal interactions between TAs and students. Four TAs (Hydrogen, Helium, Lithium, and Beryllium) were observed teaching two different laboratory activities; all other TAs were observed teaching only one laboratory activity.

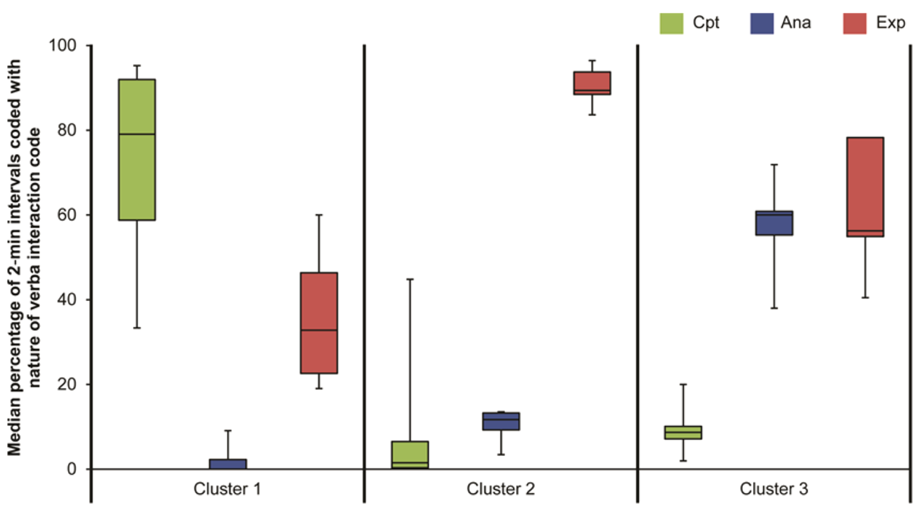

Figure 9. Median percentages of nature of verbal interaction codes for clusters identified in Figure 8.

Table 7. Relationships between the nature of verbal interaction, the nature of laboratory activities, and TAs' instructional styles

		Percentage (%) of Laboratory Activities by						
		Nature of Laboratory Activity			*Instructional Style*			
Nature of Verbal Interaction	Number of Laboratory Activities	Conceptual	Procedural	Procedural/ Analytical	Waiters	Busy bees	Observers	Guides-on-the-Side
Conceptual	4	100	0	0	25	50	0	25
Experimental	6	17	67	17	17	33	33	17
Analytical	9	0	0	100	33	11	22	33

this table revealed that there is no relationship between the nature of verbal interactions and TA's instructional styles. Indeed, videos in each verbal interaction cluster depicted at least three different TA's instructional styles. However, there is a relationship between the nature of the verbal interactions and the nature of the laboratory activity. Indeed, the conceptual verbal interaction cluster only contained videos from conceptual laboratory activities and the analytical verbal interaction cluster only contained laboratory activities with significant amount of data analysis and calculations; the majority of videos in the experimental verbal interaction cluster (67%) corresponded to procedural laboratory activities. Therefore, these results indicate that the focus of the laboratory activity drove the type of knowledge TAs and students discussed, even though opportunities to discuss each type of knowledge was present in each laboratory activity. Indeed, each laboratory activity had some underlying conceptual understanding that students should have reflected on. Our data indicates that unless the laboratory activity specifically addressed it, TAs and students did not talk about it.

DOI: 10.1021/acs.jchemed.6b00062
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DISCUSSION AND IMPLICATIONS

The goal of this study was to characterize the instructional environment experienced by undergraduate students enrolled in the laboratory component of a traditional General Chemistry course. Instrument development and analyses were grounded in the understanding that characterizing instructional practice requires the study of instructors, students, instructional materials, and their interactions.[48]

A cluster analysis of TAs' behaviors coded using LOPUS revealed four instructional styles among the 15 TAs involved in the study: Waiters, Busy bees, Observers, and Guides-on-the-side. Although these instructional styles may be specific to the context investigated and additional or different instructional styles may be observed in other settings, this study demonstrates that LOPUS enables the detailed characterization of pedagogical variations among TAs implementing the same curriculum, an outcome difficult to achieve by other laboratory-based observation protocols. Studies investigating STEM faculty's instructional practices have found variations in their implementation of specific research-based teaching strategies, which can lead to variations in student outcomes.[75−79] LOPUS can thus provide critical insight in studies investigating the effectiveness of a specific laboratory curriculum by relating TAs' variations in implementation and student outcomes.

We observed instructional style to vary among TAs despite implementation of an identical curriculum and exposure to an identical training program. Our findings are consistent with the literature describing factors influencing instructional decisions and behaviors. This literature has identified relationships between the roles of personal practical theories (i.e., beliefs about teaching and learning, self-image, and pedagogical content knowledge)[50,51] and instructional practices.[22,37,57−59] For example, a recent study investigating untrained chemistry tutors' instructional practices revealed that tutors' perceptions of tutees and their role as tutors were related to their instructional behaviors.[80] Investigations characterizing the relationships between TAs' instructional practices and their personal practical theories should be conducted in order to characterize critical influences on TAs' instructional practices. The results of such studies would provide valuable insights to designers and implementers of TA training programs.

Interactions between TAs' and students' behaviors were also investigated. First, we found that students' behaviors were independent of TAs' instructional styles, a finding that contradicts our conceptual framework for this study. Indeed, students' behaviors had limited variability across all observations: they were performing the activity, initiating conversation with, and asking questions to the TA. Since the conceptual framework was thought of within the context of instructional reform, but our study was conducted in a business-as-usual environment, it is possible that the interaction between TA's and students' behaviors is more limited in this latter context. Second, we found that TA−student verbal interactions were one-sided: TAs, regardless of their instructional style, initiated less verbal interactions with students than students did with TAs. This lack of TA-initiated interactions with students should be probed further. Studies should be conducted to unravel TAs' pedagogical knowledge (i.e., identify the extent to which they are aware of various pedagogical strategies and their impact on student learning) and reasons behind their instructional decisions. For example, TAs may have never experienced a laboratory environment in which the instructor engaged students during small group activities and therefore may not think it is necessary or may not know how to effectively do it; they may also refrain from asking questions while students are working in group because they feel it is intrusive and distracting to the students. Results of such investigations would benefit the design of TA training programs.

Finally, we investigated the relationship between the nature of the laboratory activities and TAs' instructional styles and the nature of TA−student verbal interactions. We found that instructional styles were independent of the nature of the laboratory activity. However, the nature of verbal interactions (i.e., conceptual, analytical, experimental) was related to the nature of the laboratory activity. These results confirm prior reports of the link between instructional materials and the nature of discussion between instructors and students.[21,65] They further demonstrate the need to pay close attention to the design and focus of instructional materials.

FUTURE DIRECTIONS

This study demonstrated the potential for LOPUS to provide a detailed, unbiased description of instructional practices in the laboratory. However, to further validate its sensitivity to different laboratory instructional contexts, LOPUS should be implemented in other STEM fields, under different pedagogical approaches to laboratory curriculum, and within a context of reform to training programs.

Another purpose of LOPUS beyond its use as a research tool is to serve as a real-time formative feedback tool to TAs and facilitators of TA training programs. Indeed, studies have found that TAs received insufficient pedagogical training.[81,82] For example, in the 2013 survey of graduate students conducted by the ACS, only 64.3% and 44.9% of the graduate students who had access to TA training and teaching/pedagogy workshops, respectively, found them useful.[30] Observations of TAs' instructional behaviors can inform their training by providing actionable feedback and encouraging reflections on documented instructional behaviors.[43,44] Moreover, they can inform the development and refinement of curriculum activities through the examination of how the laboratory curriculum is enacted.[44,83] Future studies should thus investigate the extent to which LOPUS can be effectively used as a professional development tool within the context of TA training programs.

LIMITATIONS

A limitation of the findings presented in this study is a TA-focused description of instructional practices. This limitation comes from the design of the data collection: the microphone was only placed on TAs and thus only recorded TAs as well as students close to the microphone but not students interacting within their groups. Therefore, student−student conversations, which may provide insights into how students undergo sense-making during the laboratory activity, could not be captured. This limitation also comes from the design of LOPUS, which examines students' behaviors at the whole class level rather than focusing on students when they are working in small groups. Interestingly, Niedderer et al. found that students express more of their knowledge, particularly their conceptual knowledge, in the presence of the TA.[33] If students in our study similarly expressed conceptual knowledge primarily when engaging with a TA, then the impact of a TA-focused observation is likely attenuated.

DOI: 10.1021/acs.jchemed.6b00062
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A second limitation of the study is the sample being investigated. The results of the study are based on a small number of videos ($N = 19$), all from the same General Chemistry curriculum implemented at one institution. Moreover, each TA was observed only once or twice. The instructional styles observed are thus not generalizable to other environments. We are currently collecting videos in the Organic Chemistry curriculum, but we hope that other researchers will replicate this study in other settings, with several observations per TA in order to provide a more in-depth understanding of the learning environments provided in chemistry laboratories at the post-secondary level and investigate the generalizability of the findings presented in this study.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00062.

LOPUS with full definitions of each code, a snapshot of LOPUS in the GORP web-app, and figures presenting the intersection between nature of verbal interaction and types of TA−student verbal interactions (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

J.B.V, A.K, D.X, T.L.V were partially supported by the National Science Foundation under Grant No. DUE-1256003. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. M.A. was supported through funding from the American Chemical Society SEED project. We would like to thank the Tools for Evidence-based Action (TEA) Development Community for supporting LOPUS and its web implementation. We would also like to thank the TAs and their students who volunteered to be videotaped.

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