The Relationship between Perceptions of Instructional Practices and Student Self-Efficacy In Guided-Inquiry Laboratory Courses

Christopher W. Beck†* and Lawrence S. Blumer‡
†Department of Biology, Emory University, Atlanta, GA 30322; ‡Department of Biology, Morehouse College, Atlanta, GA 30314

ABSTRACT
Science self-efficacy, a student's confidence in being able to perform scientific practices, interacts with science identity and outcomes expectations, leading to improved performance in science courses, persistence in science majors, and ultimately, the pursuit of advanced training in the sciences. Inquiry-based laboratory courses have been shown to improve undergraduate student self-efficacy, but the mechanisms involved and specific components of instructional practices that lead to improved self-efficacy are not clear. In the current study, we determined whether student and faculty perceptions of laboratory instructional practices (scientific synthesis, science process skills, and instructor-directed teaching) were related to postsemester self-efficacy across 19 guided-inquiry laboratory courses from 11 different institutions. Self-efficacy related to science literacy increased significantly from the beginning of the semester to the end of the semester. Variation in individual student perceptions of instructional practices within a course were significantly related to differences in student self-efficacy at the end of the semester, but not average student perceptions or faculty perceptions of their own practices across courses. The importance of individual student perceptions suggests that faculty should engage with students during curricular development. Furthermore, faculty need to use noncontent talk to reinforce the science practices students are engaging in during inquiry-based laboratory courses.

INTRODUCTION
Self-efficacy (specifically science self-efficacy or research self-efficacy) is an individual's confidence in their ability to perform tasks, scientific activities, and work like a scientist successfully (Byars-Winston *et al.*, 2016). Research self-efficacy (Bandura, 1986; Usher and Pajares, 2008; Trujillo and Tanner, 2014) develops as a result of four factors: performance accomplishments (past successes or mastery), vicarious learning (e.g., observing the behavior of role models), social persuasion (encouragement by others), and affective/emotional arousal (minimal anxiety when performing research tasks). Self-efficacy is viewed as a central component in models of social cognitive career theory (SCCT; Lent *et al.*, 1994), in which the development and maintenance of long-term interest in an activity results when an individual views themself as capable of performing the activity (positive self-efficacy), and the activity leads to valued outcomes. In addition to playing a central role in career outcomes, self-efficacy may be related to science identity and outcomes expectations, which in turn may influence career outcomes (Eccles, 2009; Byars-Winston *et al.*, 2016). Self-efficacy, science identity, and outcomes expectations are suggested to interact and to mediate either directly or indirectly the ultimate outcomes of science interests, career goals, and actions (see Figure 1 in Byars-Winston *et al.*, 2016). Importantly, in Byars-Winston and colleagues' (2016) modified SCCT model, research self-efficacy, science identity, and outcome

Brian Sato, *Monitoring Editor*
Submitted Apr 23, 2020; Revised Oct 9, 2020; Accepted Oct 27, 2020
CBE Life Sci Educ March 1, 2021 20:ar8
DOI:10.1187/cbe.20-04-0076
*Address correspondence to: Christopher W. Beck (cbeck@emory.edu).

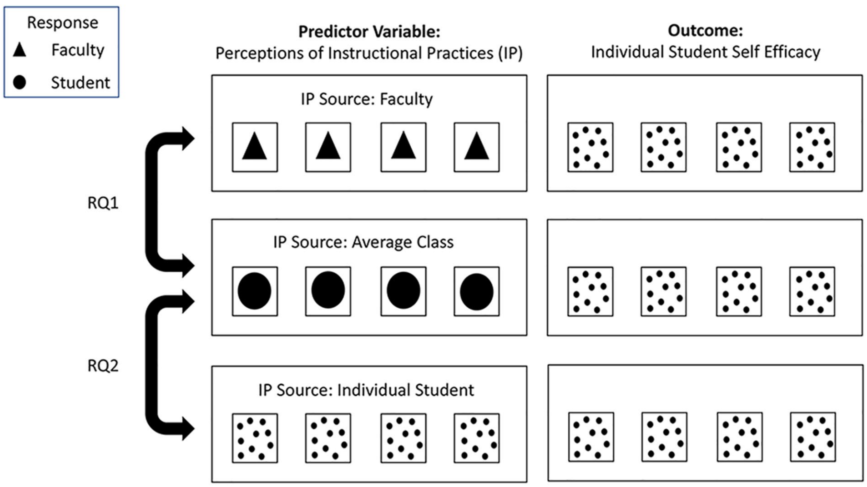

FIGURE 1. Schematic diagram of the experimental design used in this study. The potential influence of perceptions of instructional practices (IP) on postsemester student self-efficacy was evaluated in three separate models (faculty perceptions, average student perceptions, and individual student perceptions). In this schematic representation, the boxes on the right and left sides represent the same pool of participating laboratory courses ($N = 19$, with only 4 depicted for clarity), with squares representing independent courses. Faculty and student perceptions of IP were assessed in each laboratory course. In addition, individual student self-efficacy was assessed at the end of each of these laboratory courses (outcome variable, small circles representing each individual student on right side of diagram). We developed three statistical models using perceptions of IP to predict student self-efficacy outcomes. In the first model, faculty IP perceptions (represented by the one large triangle per course) were the predictor variable. In the second model, the average student IP perceptions in each course (represented by the one large circle per course) were the predictor variable. In the third model, individual student IP perceptions within each course (represented by multiple small circles per course) that were course-mean centered were the predictor variable. Research question 1 (RQ1) explored whether faculty or student perceptions of IPs better predicted student self-efficacy. Research question 2 (RQ2) explored whether student self-efficacy was better predicted by differences among courses (average student perception) or variation among students within a course (individual student perception).

expectations are affected by learning experiences, which suggests that instructional practices in courses have the potential to influence changes in self-efficacy. Although many factors can influence student learning experiences, focusing on instructional practices, the part of the learning experience that is most closely controlled by instructors, is appropriate, because it also is the component of learning experiences that instructors can most readily modify to improve student outcomes.

Inquiry-based laboratory courses are known to lead to improved student outcomes relative to traditional laboratory courses (reviewed by Beck *et al.*, 2014). In particular, increases in student self-efficacy have been documented in laboratory courses across a range of disciplines in the context of inquiry-based pedagogy. For example, Dohn *et al.* (2016) showed increases in self-efficacy in an inquiry-based physiology laboratory course. Similarly, we found increases in student self-efficacy in scientific inquiry skills in inquiry-based upper-level ecology laboratory courses across multiple semesters at two different institutions (a private research university and a historically black, all-male, liberal arts college; Beck and Blumer, 2012). Inquiry-based chemistry laboratory courses also result in increased student self-efficacy (e.g., Winkelmann *et al.*, 2015; Heider *et al.*, 2018).

Mentored and course-based undergraduate research experiences (CUREs) also can lead to increased student self-efficacy (Seymour *et al.*, 2004; Corwin *et al.*, 2015a). For instance, in a mentored research program across science, technology, engineering, and mathematics (STEM) disciplines, student self-efficacy related to research skills increased and was positively related to students' intentions of pursuing a career in research (Adedokun *et al.*, 2013). These structured mentored research programs positively impact self-efficacy for students who are traditionally underrepresented in STEM (Hurtado *et al.*, 2009; Carpi *et al.*, 2017). CUREs also can result in increases in student self-efficacy, especially compared with non-CURE laboratory courses (e.g., Olimpo *et al.*, 2016; Hanauer *et al.*, 2017, 2018; Esparza *et al.*, 2020).

Although inquiry-based laboratory courses, CUREs, and mentored research influence student self-efficacy, what aspects of these experiences or how these experiences lead to increases in self-efficacy is less clear (Beck *et al.*, 2014; Corwin *et al.*, 2015a; Dolan, 2015). For example, Frantz *et al.* (2017) found similar increases in self-efficacy related to scientific research when comparing students in a mentored research program with those in a collaborative research program similar to a CURE, suggesting that differences between these types of experiences are unimportant in fostering the development of self-efficacy. Similarly, when comparing self-efficacy of students who are not biology majors in laboratory courses with differing degrees of discovery and relevance, which are often considered essential components of a CURE (Auchincloss *et al.*, 2014), Ballen *et al.* (2018) found no differences in self-efficacy (but see Corwin *et al.*, 2018a). Because approaches to inquiry and authentic research in laboratory courses can vary (Auchincloss *et al.*, 2014; Beck *et al.*, 2014; Spell *et al.*, 2014; Staub *et al.*, 2016), understanding what components of these courses contribute to improved student outcomes is essential. For example, in a study of 49 CUREs at seven institutions, Mader *et al.* (2017) reported greater gains in courses in which students and faculty did not know the results of the research in advance and in which students had greater autonomy in asking the research question or designing the experiment. Similarly, in an analysis of several CUREs and the Freshman Research Initiative at the University of Texas, Austin, Corwin *et al.* (2018b) found that discovery, collaboration, and iteration all positively influenced students' perceptions of ownership, with iteration having the largest effect. More recently, Esparza *et al.* (2020) showed that different instructor and student behaviors were related to different student affective outcomes in CURE and non-CURE classes. Student self-efficacy was positively related to instructor interactive behaviors (such as questioning and one-on-one dialogue) and instructor typical behaviors with a negative interaction between these two factors. In contrast, student intrinsic motivation was negatively related to both instructor and student interactive behaviors with a positive interaction between the two factors.

The specific instructional practices in inquiry-based laboratory courses that influence students' self-efficacy or how these courses lead to increases in self-efficacy is unclear. Therefore, in this study, we investigated whether the degree to which science practices were emphasized by faculty influenced student self-efficacy. Here, we focused on self-efficacy as related to science literacy (ability to pose questions, design experiments, evaluate evidence, and apply scientific information) in the context of guided-inquiry courses across a range of institutions and course levels. Previous research suggests that science literacy increases due to participation in inquiry-based laboratory courses (Gehring and Eastman, 2008; Gormally *et al.*, 2009). As a result, we predicted that student self-efficacy related to science literacy would increase for individual students from the beginning to the end of the semester in the guided-inquiry laboratory courses in our study. Furthermore, we predicted that increases in self-efficacy would be greater in those courses that emphasized science practices to a greater degree, because these courses would provide mastery experiences known to increase self-efficacy (Usher and Pajares, 2008; Trujillo and Tanner, 2014; Flowers and Banda, 2016).

To explore the relationship between instructional practices in guided-inquiry laboratory courses and student self-efficacy, we needed to examine instructional practices across a range of courses. A variety of instruments have been developed to examine teaching in laboratory courses (Campbell *et al.*, 2010; Corwin *et al.*, 2015b; Beck and Blumer, 2016; Velasco *et al.*, 2016). As student self-efficacy is mediated by student experiences (Bandura, 1986; Usher and Pajares, 2008; Trujillo and Tanner, 2014), we wanted to use an instrument that captured students' perceptions of instructional practices (Campbell *et al.*, 2010; Corwin *et al.*, 2015b; Beck and Blumer, 2016), rather than an observational protocol (Velasco *et al.*, 2016). In addition, the instrument needed to capture the range of instructional practices that can occur in a guided-inquiry laboratory course. Our previously published survey of instructional practices (Beck and Blumer, 2016) was designed to align with the different aspects of inquiry-based learning defined in the National Science Education Standards (National Research Council, 1996). In addition, it included items integral to some types of inquiry-based learning in laboratory courses (D'Avanzo and McNeal, 1997; Flora and Cooper, 2005; Weaver *et al.*, 2008), such as whether students generate their own experimental designs and whether the outcomes of experiments were determined in advance. In contrast, the survey developed by Corwin *et al.* (2015b) determines the degree to which aspects that are unique to CUREs occur in laboratory courses.

We examined the relationship between instructional practices and student self-efficacy in 19 courses across 11 institutions. Because instructional practices in a course can be viewed from the perspective of an instructor and the perspective of their students, we specifically wanted to examine whether faculty or student perceptions of instructional practices better predicted student self-efficacy across courses (research question 1; Figure 1). Previous studies indicate that faculty and student perceptions of instructional practices do not always align (e.g., Jaskyte *et al.*, 2009; Beck and Blumer, 2016), suggesting that faculty and student perceptions might differ in their relationships with student self-efficacy.

In a scale-up study with data from multiple courses across a range of institutions, variation in student perceptions of instructional practices can be due to differences among courses, variation among students in the same course, or both. Therefore, to examine the relationship between student perceptions of instructional practices and self-efficacy in more detail, we explored whether student self-efficacy was better predicted by differences among courses (average student perception) or variation among students within a course (individual student perception; research question 2; Figure 1).

METHODS

The students in the current study took laboratory courses in which a guided-inquiry module using the bean beetle (*Callosobruchus maculatus*) model system was implemented. Details on the professional development of faculty who taught the laboratory courses and a general description of the laboratory courses taken by the students in the current study are described in Beck and Blumer (2019) and Blumer and Beck (2019), respectively.

To examine student self-efficacy related to science literacy, we used a standard pretest/posttest approach. Students completed the pretest and posttest on paper during the first and last weeks of the semester, respectively. The survey included 12 Likert-scale items from an instrument developed by Champagne (1989) that probes students' confidence in their ability to pose questions, design experiments, evaluate evidence, and apply scientific information (see Supplemental Material). The five-point Likert scale ranged from 1, not confident, to 5, very confident. The 12 items represent a single construct with high reliability based on pretest scores (Cronbach's alpha = 0.94).

To determine the instructional practices in the laboratory courses, we surveyed both faculty and students using a laboratory instructional practices survey (Beck and Blumer, 2016). The data on instructional practices in the current study were a subset of those previously described in Beck and Blumer (2016). In the current study, we focused on those constructs most closely related to science practices (scientific synthesis, science process skills, and instructor-directed teaching; see Supplemental Table S1 for the items in each construct).

A total of 479 students from 35 courses at 15 different institutions were initially included in the study. Our sample included students from a broad range of institution types, including one minority-serving institution, and all course levels (nonmajors, introductory biology majors, and upper-level biology majors; Table 1). Students included those self-identifying as male (35%) and female (65%), as well as underrepresented minorities (URM; students self-identifying a racial or ethnic group other than Asian or white; 20%) and non-URMs (80%; Table 1). URM status was based on students selecting a race/ethnicity category (Asian, Black/African American, Hispanic, Native American/Alaskan Native, white, multiracial, prefer not to answer, other). Students of different URM status and different genders were not evenly distributed across courses. As a result, we did not include student demographics in our analyses to avoid

TABLE 1. Distribution of institutions, courses and students completing the self-efficacy and instructional practices assessments[a]

Number of institution types	Liberal arts colleges	Regional comprehensive university	Community college
	6	3	2
Number of course types at each institution type			
Non-biology majors	1	0	2
Introductory biology	6	3	1
Upper-level biology	2	4	0
Minority-serving institution	0	1	0
Primarily white institution	6	2	2
	Non-biology majors	**Introductory biology**	**Upper-level biology**
Total number of each course type	3	10	6
Students in each course type	43	192	95
Number of students	**Males**	**Females**	**Not reported**
	112	208	10
	URM[b]	**Non-URM**	**Not reported**
	64	255	11

[a]Institution types were defined as liberal arts colleges (4-yr undergraduate but no graduate programs), regional comprehensive university (4-yr undergraduate and graduate degree programs), and community college (2-yr undergraduate programs).
[b]URM, self-reported identification as an underrepresented minority

confounding demographic effects with course effects. This study was approved by the institutional review boards at Emory University (IRB no. 00010542) and Morehouse College (IRB no. 025), as well the participating institutions, when required.

Statistical Analyses

To examine whether student self-efficacy changed during a one-semester course, we compared presemester and postsemester scores with a paired t test for the entire sample. Effect size was calculated as Cohen's d for paired samples. We examined the relationship between instructional practices and end-of-semester student self-efficacy (postsemester self-efficacy) to determine whether faculty perceptions or student perceptions were better predictors of self-efficacy. Absolute change in student self-efficacy (postsemester minus presemester self-efficacy) also was calculated, but the relationships between perceptions of instructional practices and student self-efficacy were the same whether evaluating absolute change in self-efficacy or simply the postsemester self-efficacy (see Supplemental Table S3). Consequently, we focus on end-of-semester student self-efficacy in the analysis that follows.

Because we were interested in differences among courses as well as variation within courses, we used a series of hierarchical linear mixed-effects models to control for the fact that students within a course and courses within an institution are not independent of one another (Theobald, 2018). To determine the most appropriate random effects to include in our models, we constructed a series of null models that only included random effects. As some instructors within an institution taught multiple courses in our sample, we started with a three-level null model with instructor nested within institution and course nested within instructor as random effects. However, the model fit was singular, indicating that the model was overparameterized. This overparameterization was likely due to the fact that most instructors in our sample taught only one course (10 of 14 instructors) and therefore course and instructor were largely redundant. Consequently, we compared two two-level null models (instructor nested within institution and course nested within institution as random effects) to determine whether course or instructor explained more of the variation in self-efficacy. Instructor nested within institution explained 3% of the variation in self-efficacy, whereas course nested within institution explained 4.3% of the variation in self-efficacy. Therefore, we used course nested within institution as a random effect in our subsequent models to control for the non-independence of students within a course.

Any student outcome measure at the end of the semester is often influenced by student scores on that measure at the beginning of the semester (Theobald and Freeman, 2014). For example, students with high self-efficacy at the beginning of the semester are likely to show higher self-efficacy at the end of the semester compared with students with low self-efficacy at the beginning of the semester. Therefore, we included presemester self-efficacy as a covariate in all of our models (Theobald and Freeman, 2014). Our sample included students in courses at multiple different levels, and course level has the potential to influence postsemester self-efficacy for many reasons, including differences in presemester self-efficacy among students at different course levels or the nature of the courses at different levels. To determine the effect of course level on postsemester self-efficacy and whether course level should be included as a covariate in subsequent analyses, we compared a model with just presemester self-efficacy as an explanatory variable against a model with presemester self-efficacy and course level as explanatory variables. The second model was originally fit with an interaction effect between presemester self-efficacy and course level (Beck and Bliwise, 2014), but the interaction was removed from the final model because it was not significant ($X^2 = 2.11$, $df = 2$, $p = 0.35$). The simpler model with just presemester self-efficacy as a covariate was a better model than a model that included course level, based on minimizing Akaike information criterion (AIC; Table 2), so course level was excluded from subsequent models.

TABLE 2. Hierarchical linear models to explain postsemester student self-efficacy related to science literacy[a]

Model name	Model	AIC
Null	Postsemester_self_efficacy ~ (1|institution/course)	807.1
Single covariate	Postsemester_self_efficacy ~ presemester self_efficacy + (1|institution/course)	713.9
Two covariates	Postsemester_self_efficacy ~ presemester self_efficacy + level + (1|institution/course)	717.4
Faculty perceptions	Postsemester_self_efficacy ~ presemester self_efficacy + f_scientific synthesis + f_science process skills + f_instructor-directed teaching + (1|institution/course)	719.7
Average student perceptions	Postsemester_self_efficacy ~ presemester self_efficacy + as_scientific synthesis + as_science process skills + as_instructor-directed teaching + (1|institution/course)	718.5
Individual student perceptions	**Postsemester_self_efficacy ~ presemester self_efficacy + s_scientific synthesis + s_science process skills + s_instructor-directed teaching + (1|institution/course)**	**629.9**

[a]The last three models include faculty, average student, or individual student perceptions of instructional practices, respectively. The faculty perceptions model examined differences in faculty perceptions of instructional practices among courses and their relationship with postsemester self-efficacy. The average student perceptions model examined differences in student perceptions of instructional practices among courses and their relationship with postsemester self-efficacy. The individual student perceptions model examined differences in student perceptions of instructional practices within courses and their relationship with postsemester self-efficacy. The best model is indicated in bold. Note that, based on AIC, the single covariate model is a better model than both the faculty perceptions and average student perceptions models. $N = 330$ for all models.

We determined the effect of faculty and student perceptions of instructional practices on postsemester student self-efficacy related to science literacy by comparing three separate statistical models (Figure 1, Table 2). The faculty perceptions and average student perceptions models examined differences in faculty or student perceptions of instructional practices among courses, respectively, and their relationship with postsemester self-efficacy. In contrast, the individual student perceptions model examined differences in student perceptions of instructional practices within courses and their relationship with postsemester self-efficacy. To construct the individual student perceptions model, we determined the deviation of individual students' perceptions of the three instructional practices by subtracting the course mean value from the individual student values for each instructional practice (i.e., calculated course-mean centered values). Course-mean centered values maintain the variation among individual students within a course but shift the distribution such that the mean is zero for all courses, allowing for exploration of the effect of within-course variation independent of differences among courses. These course-mean centered values for individual students were used as the independent predictor variables in the individual student perceptions model. To address whether faculty or student perceptions of instructional practices better predicted student self-efficacy across courses (research question 1), we compared the faculty perceptions and average student perceptions models. To determine whether student self-efficacy was better predicted by differences among courses (average student perceptions) or variation among students within a course (individual student perceptions; research question 2), we compared the average student perceptions and individual student perceptions models.

All hierarchical linear models were fit using maximum likelihood implemented with the lme4 package in R (Bates *et al.*, 2015). We compared all models using AIC (Table 2). The model that minimized AIC was considered the best model. We examined the effect of the different aspects of instructional practices on postsemester self-efficacy by estimating *p* values for the fixed effects using the car package in R (Fox and Weisberg, 2019).

RESULTS

Across all courses, student self-efficacy related to science literacy increased significantly from the beginning of the semester to the end of the semester in the context of participating in a guided-inquiry laboratory ($t = 12.23$, $df = 329$, $p < 0.0001$, $d = 0.67$; Figure 2). Average values increased from 3.16 (i.e., just above a level of "confident") to 3.72 (i.e., just below the intermediate value between "confident" and "very confident"). The presemester level of self-efficacy was positively related to postsemester self-efficacy (Table 3), and significant increases in self-efficacy occurred for all students, except those whose presemester self-efficacy was in the highest quartile (Supplemental Figure S1 and Supplemental Table S2).

When comparing the faculty perceptions and average student perceptions models (research question 1), the models were similar based on AIC, and neither was the best model (Table 2). Both models were no better (indeed worse) than the model with only presemester self-efficacy as a covariate (one covariate model) based on AIC (Table 2). As a result, none of the instructional practices were significantly related to self-efficacy for these models (Table 3). When comparing the average student perceptions and individual student perceptions models (research question 2), the best model was the individual student perceptions model (Table 2). In fact, the individual student perceptions model was the best model overall (Table 2). In the individual student perceptions model, scientific synthesis and science process skills had significant positive effects on self-efficacy (Table 3). In other words, within a course, students who

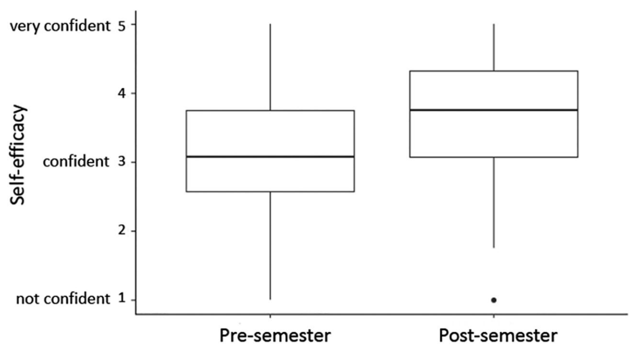

FIGURE 2. Increase in student self-efficacy from beginning to the end of the semester in guided-inquiry laboratory courses.

TABLE 3. Parameter estimates for the relationships between perceptions of instructional practices and postsemester student self-efficacy[a]

	Estimate	SE	*t* value	*p* value
Faculty perceptions				
Intercept	**2.37**	**0.58**	**4.04**	**<0.01**
Presemester self-efficacy	**0.48**	**0.05**	**9.58**	**<0.001**
Scientific synthesis	0.04	0.26	0.16	0.88
Science process skills	–0.05	0.22	–0.21	0.84
Instructor-directed teaching	–0.07	0.15	–0.46	0.65
Average student perceptions				
Intercept	1.15	1.26	0.92	0.37
Presemester self-efficacy	**0.47**	**0.05**	**9.50**	**<0.001**
Scientific synthesis	0.67	0.58	1.16	0.27
Science process skills	–0.25	0.48	–0.53	0.6
Instructor-directed teaching	–0.13	0.31	–0.41	0.69
Individual student perceptions				
Intercept	**2.29**	**0.15**	**15.55**	**<0.001**
Presemester self-efficacy	**0.45**	**0.04**	**10.35**	**<0.001**
Scientific synthesis	**0.49**	**0.10**	**4.75**	**<0.001**
Science process skills	**0.23**	**0.09**	**2.50**	**0.01**
Instructor-directed teaching	0.13	0.07	1.83	0.07

[a]The best model based on AIC is the individual student perceptions model (see Table 2). Significant effects are indicated in bold. $N = 330$ for all models.

perceived that they participated more often in scientific synthesis and science process skills than the average student in the same course exhibited significantly greater end-of-semester self-efficacy. The effect was greatest for scientific synthesis. Instructor-directed teaching had no significant effect on student self-efficacy (Table 3).

Differences in the predictive ability of the three models that examined the effects of instructional practices on student self-efficacy might have been due to differences in the degree of variation in perceptions of instructional practices among courses versus within courses. To test this hypothesis, we calculated the coefficient of variation across courses for each of the instructional practices as appropriate for the different models (faculty, average student, individual student). The degree of variation was similar for faculty and individual student perceptions, but substantially lower for average student perceptions (Supplemental Figure S2), suggesting that differences in the predictive ability of the different models was unrelated to the degree of variation in the perceptions of instructional practices.

DISCUSSION

Mentored research experiences, CUREs, and inquiry-based laboratory courses influence student self-efficacy (e.g., Beck and Blumer, 2012; Adedokun *et al.*, 2013; Dohn *et al.*, 2016; Olimpo *et al.*, 2016; Hanauer *et al.*, 2017, 2018). Similarly, in the current study, we found significant increases in student self-efficacy related to science literacy in guided-inquiry laboratory courses across a range of institutions and course levels. Student self-efficacy or confidence in their science literacy increased from "confident" at the beginning of the semester to between "confident" and "very confident" at the end of the semester.

Previous studies have examined the effect of instructional practices on student outcomes in biology laboratory courses (Mader *et al.*, 2017; Corwin *et al.*, 2018b; Esparza *et al.*, 2020). In these studies, instructional practices were determined based on student surveys (Corwin *et al.*, 2018b), faculty surveys (Mader *et al.*, 2017), or expert observation (Esparza *et al.*, 2020). In the current study, we examined whether faculty perceptions, average student perceptions, or individual student perceptions were the best predictors of student self-efficacy. We found that differences in faculty and student perceptions of instructional practices across courses were not significantly related to student self-efficacy. In contrast, individual student perceptions of instructional practices related to scientific synthesis and science process skills within a course were the most predictive of student self-efficacy. Ultimately, learning is an individual process, so not surprisingly, individual perceptions matter. We speculate that individual perceptions of science process skills may be linked to individual variation in vicarious experiences, which is known to influence self-efficacy (Usher and Pajares, 2008; Trujillo and Tanner, 2014; Flowers and Banda, 2016). Vicarious experiences such as observing fellow students engaging the initial steps of science practices (posing a question, developing testable hypotheses, stating unambiguous predictions, and designing an experiment to test hypotheses) are the activities that differentiate inquiry-based laboratory pedagogy from traditional laboratory teaching and learning.

Variation between students in their individual perceptions of science practices also may be an indicator of the level of engagement of individuals in their laboratory work. Less engagement would mean less direct contribution to the scientific study being conducted, and therefore a lower level of mastery experiences in the context of the laboratory course. These differences among students in engagement in mastery experiences might result in lower individual perceptions of science practices, which in turn could lead to lower gains in self-efficacy. Engagement may be diminished when students are working in groups that are too large or in cases in which laboratory partners are not equally sharing responsibilities for conducting their laboratory work.

In our study, not all instructional practices contributed equally to postsemester self-efficacy. Individual students' perceptions of scientific synthesis had greater effects on self-efficacy than their perceptions of science process skills, but both were significant. Similarly, Corwin *et al.* (2018b) found different impacts among aspects of CURE pedagogy on students' sense of ownership. In particular, iteration had the greatest effect on ownership. The difference we found in the effects of scientific synthesis and science process skills on self-efficacy may be a consequence of the specific questions in the self-efficacy instrument we used (see Supplemental Material), as more items addressed scientific synthesis rather than science process skills. Using a different self-efficacy instrument with items that more closely related to science process skills (posing questions, developing hypotheses, and experimental design) might have yielded the opposite relationship. In short, which components of inquiry-based laboratory courses or CUREs are most important in affecting student outcomes likely depends on the outcomes measured and how they are measured. In fact, Esparza *et al.* (2020) found that the effect of faculty and student behaviors in CUREs varied for different student affective outcomes. Additional studies that examine multiple outcomes simultaneously would be helpful in exploring how the relationship between instructional practices and student outcomes differs based on what outcomes are measured.

Our experimental design did not allow us to determine whether differences in individual student perceptions of instructional practices caused the differences in self-efficacy. However, we suggest that student perceptions of instructional practices likely lead either directly or indirectly to changes in self-efficacy. This view is consistent with the theory that self-efficacy develops as a result of student experiences (Bandura, 1986; Usher and Pajares, 2008; Trujillo and Tanner, 2014). In addition, the directionality from instructional practices to self-efficacy is consistent with models of student outcomes in CUREs (Corwin *et al.*, 2015a), as well as empirical studies on the effects of CURE components on student outcomes (Corwin *et al.*, 2018b).

In the current study, individual students' perceptions of instructional practices influenced postsemester self-efficacy related to science literacy. In contrast, average student perceptions of instructional practices across courses were not significantly related to postsemester self-efficacy. This suggests that variation in perceptions among students within a course are more important than between-course differences in explaining student self-efficacy in our sample. Variation across courses was substantially lower than variation within courses (Supplemental Figure S2), which might have led to this result. Future studies that examine courses that implement a broader range of instructional practices would allow us to further explore the relative importance for student outcomes of within- and between-course variation in student perceptions of instructional practices.

Although the lack of a significant relationship between average student perceptions of instructional practices and self-efficacy could be due to low levels of variation across courses, faculty perceptions of the instructional practices that they used in their laboratory courses also were unrelated to student self-efficacy, despite substantially higher variation in perceptions of instructional practices at the faculty level (Supplemental Figure S2). The disconnect between faculty perceptions of instructional practices and student self-efficacy suggests that the intentions of the faculty have little or no influence on student outcomes. As a result, effective learning interventions must focus on student perceptions and changing student perceptions. Making laboratory pedagogy transparent and intentional may be key to student perceptions of science practices. We suggest that faculty should actively engage students in their laboratory classes in the curricular development and assessment process. Students should be told when a course activity is new or under development and that they will be helping to improve learning by engaging in the proposed activity. The learning process should become transparent to students through faculty discussing the intended purpose of specific activities, the specific science practices that will be developed, and the real-world value of those practices. Such non-science discussion of the learning process may be important for influencing student outcomes (Silverthorn, 2006; Seidel *et al.*, 2015). The mediator of these positive effects is a change in student perceptions of faculty intentions. By explicitly discussing the learning process with students and potentially changing student perceptions of faculty intentions, variation in student perceptions of instructional practices among students within a class would likely decrease, leading to similar gains in self-efficacy for all students.

While we found that individual student perceptions of instructional practices influence student self-efficacy, whether instructional practices are related to medium- and long-term outcomes is less clear. Self-efficacy has been shown to be correlated with science identity, retention in STEM majors, and science career goals in some studies (Hurtado *et al.*, 2009; Chemers *et al.*, 2011; Estrada *et al.*, 2011; Adedokun *et al.*, 2012; Findley-Van Nostrand and Pollenz, 2017). Yet, self-efficacy was unrelated to postbaccalaureate persistence in STEM in other studies (e.g., Estrada *et al.*, 2018). Future research that examines what aspects of inquiry-based laboratory courses and CUREs increase medium- and long-term outcomes and whether those outcomes are mediated by short-term outcomes, such as self-efficacy, will allow us to further clarify the important components of laboratory courses for improving student outcomes. Such research also might consider student outcomes over a series of courses to understand whether multiple exposures of inquiry-based laboratory courses lead to greater gains in student outcomes at all timescales.

ACKNOWLEDGMENTS

We thank the faculty participants in the Bean Beetle Curriculum Development Network and their students for volunteering for this study. We also thank Dr. Anna Zelaya and two anonymous reviewers who provided extensive constructive comments for improving the article. This study and publication was funded by National Science Foundation (NSF) grants DUE-0815135, DUE-0814373, and HRD-2010676 to Morehouse College and Emory University. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the NSF.

REFERENCES

Adedokun, O. A., Bessenbacher, A. B., Parker, L. C., Kirkham, L. L., & Burgess, W. D. (2013). Research skills and STEM undergraduate research students' aspirations for research careers: Mediating effects of research self-efficacy. *Journal of Research in Science Teaching*, *50*(8), 940–951. doi: 10.1002/tea.21102

Adedokun, O. A., Zhang, D., Parker, L. C., Bessenbacher, A., Childress, A., Burgess, W. D., & Adedokun, B. O. A. (2012). Understanding how undergraduate research experiences influence student aspirations for research careers and graduate education. *Journal of College Science Teaching*, *42*, 82–90.

Auchincloss, L. C., Laursen, S. L., Branchaw, J. L., Eagan, K., Graham, M., Hanauer, D. I., ... & Dolan, E. L. (2014). Assessment of Course-Based Undergraduate Research Experiences: A Meeting Report. *CBE—Life Sciences Education*, *13*(1), 29–40. doi: 10.1187/cbe.14-01-0004

Ballen, C. J., Thompson, S. K., Blum, J. E., Newstrom, N. P., & Cotner, S. (2018). Discovery and broad relevance may be insignificant components of course-based undergraduate research experiences CUREs for non-biology majors. *Journal of Microbiology & Biology Education*, *19*(2). doi: 10.1128/jmbe.v19i2.1515

Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory*. Englewood Cliffs, NJ: Prentice-Hall.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48. doi: 10.18637/jss.v067.i01

Beck, C. W., & Bliwise, N. G. (2014). Interactions are critical. *CBE—Life Sciences Education*, *13*, 371–372.

Beck, C. W., & Blumer, L. S. (2012). Inquiry-based ecology laboratory courses improve student confidence and scientific reasoning skills. *Ecosphere*, *3*, art112.

Beck, C. W., & Blumer, L. S. (2016). Alternative realities: Faculty and student perceptions of instructional practices in laboratory courses. *CBE—Life Sciences Education*, *15*, ar52. doi: 10.1187/cbe.16-03-0139

Beck, C. W., & Blumer, L. S. (2019). A model for an intensive hands-on faculty development workshop to foster change in laboratory teaching. *Journal of Microbiology & Biology Education*, *20*(3). doi: 10.1128/jmbe.v20i3.1799

Beck, C. W., Butler, A., & Burke da Silva, K. (2014). Promoting inquiry-based teaching in laboratory courses: Are we meeting the grade? *CBE—Life Sciences Education*, *13*, 444–452.

Blumer, L. S., & Beck, C. W. (2019). Laboratory courses with guided-inquiry modules improve scientific reasoning and experimental design skills for the least-prepared undergraduate students. *CBE—Life Sciences Education*, *18*(1), ar2. doi: 10.1187/cbe.18-08-0152

Byars-Winston, A., Rogers, J., Branchaw, J., Pribbenow, C., Hanke, R., & Pfund, C. (2016). New measures assessing predictors of academic persistence for historically underrepresented racial/ethnic undergraduates in science. *CBE—Life Sciences Education*, *15*(3), ar32. doi: 10.1187/cbe.16-01-0030

Campbell, T., Abd-Hamid, N. H., & Chapman, H. (2010). Development of instruments to assess teacher and student perceptions of inquiry experiences in science classrooms. *Journal Science Teacher Education*, *21*, 13–30.

Carpi, A., Ronan, D. M., Falconer, H. M., & Lents, N. H. (2017). Cultivating minority scientists: Undergraduate research increases self-efficacy and career ambitions for underrepresented students in STEM. *Journal of Research in Science Teaching*, *54*(2), 169–194. doi: 10.1002/tea.21341

Champagne, A. B. (1989). Defining scientific literacy. *Educational Leadership*, *47*, 85–86.

Chemers, M. M., Zurbriggen, E. L., Syed, M., Goza, B. K., & Bearman, S. (2011). The role of efficacy and identity in science career commitment among underrepresented minority students. *Journal of Social Issues*, *67*, 469–491.

Corwin, L. A., Dolan, E. L., Graham, M. J., Hanauer, D. I., & Pelaez, N. (2018a). The need to be sure about CUREs: Discovery and relevance as critical elements of CUREs for nonmajors. *Journal of Microbiology & Biology Education*, *19*(3). doi: 10.1128/jmbe.v19i3.1683

Corwin, L. A., Graham, M. J., & Dolan, E. L. (2015a). Modeling course-based undergraduate research experiences: An agenda for future research and evaluation. *CBE—Life Sciences Education*, *14*(1), es1. doi: 10.1187/cbe.14-10-0167

Corwin, L. A., Runyon, C. R., Ghanem, E., Sandy, M., Clark, G., Palmer, G. C., ... & Dolan, E. L. (2018b). Effects of discovery, iteration, and collaboration in laboratory courses on undergraduates' research career intentions fully mediated by student ownership. *CBE—Life Sciences Education*, *17*(2), ar20. doi: 10.1187/cbe.17-07-0141

Corwin, L. A., Runyon, C., Robinson, A., & Dolan, E. L. (2015b). The laboratory course assessment survey: A tool to measure three dimensions of research-course design. *CBE—Life Sciences Education*, *14*(4), ar37.

D'Avanzo, C., & McNeal, A. P. (1997). Research for all students: Structuring investigation into first year courses. In McNeal, A. P., & D'Avanzo, C. (Eds.), *Student-active science: Models of innovation in college science teaching* (pp. 279–300). Fort Worth, TX: Saunders College Publishing.

Dohn, N. B., Fago, A., Overgaard, J., Madsen, P. T., & Malte, H. (2016). Students' motivation toward laboratory work in physiology teaching. *Advances in Physiology Education*, *40*(3), 313–318. doi: 10.1152/advan.00029.2016

Dolan, E. L. (2015). Biology Education Research 2.0. *CBE—Life Sciences Education*, *14*(4), ed1. doi: 10.1187/cbe.15-11-0229

Eccles, J. (2009). Who am I and what am I going to do with my life? Personal and collective identities as motivators of action. *Educational Psychologist*, *44*(2), 78–89. doi: 10.1080/00461520902832368

Esparza, D., Wagler, A. E., & Olimpo, J. T. (2020). Characterization of instructor and student behaviors in CURE and Non-CURE learning environments: Impacts on student motivation, science identity development, and perceptions of the laboratory experience. *CBE—Life Sciences Education*, *19*(1), ar10. doi: 10.1187/cbe.19-04-0082

Estrada, M., Hernandez, P. R., & Schultz, P. W. (2018). A longitudinal study of how quality mentorship and research experience integrate underrepresented minorities into STEM careers. *CBE—Life Sciences Education*, *17*(1), ar9. doi: 10.1187/cbe.17-04-0066

Estrada, M., Woodcock, A., Hernandez, P. R., & Schultz, P. W. (2011). Toward a model of social influence that explains minority student integration into the scientific community. *Journal of Educational Psychology*, *103*(1), 206–222. doi: 10.1037/a0020743

Findley-Van Nostrand, D., & Pollenz, R. S. (2017). Evaluating psychosocial mechanisms underlying STEM persistence in undergraduates: Evidence of impact from a six-day pre-college engagement STEM academy program. *CBE—Life Sciences Education*, *16*(2), ar36. doi: 10.1187/cbe.16-10-0294

Flora, J. R. V., & Cooper, A. T. (2005). Incorporating inquiry-based laboratory experiment in undergraduate environmental engineering laboratory. *Journal of Professional Issues in Engineering Education and Practice*, *131*, 19–25.

Flowers, A. M., & Banda, R. (2016). Cultivating science identity through sources of self-efficacy. *Journal for Multicultural Education*, *10*(3), 405–417. doi: 10.1108/jme-01-2016-0014

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression* (3rd ed.). Thousand Oaks, CA: Sage.

Frantz, K. J., Demetrikopoulos, M. K., Britner, S. L., Carruth, L. L., Williams, B. A., Pecore, J. L., ... & Goode, C. T. (2017). A comparison of internal dispositions and career trajectories after collaborative versus apprenticed research experiences for undergraduates. *CBE—Life Sciences Education*, *16*(1), ar1. doi: 10.1187/cbe.16-06-0206

Gehring, K. M., & Eastman, D. A. (2008). Information fluency for undergraduate biology majors: Applications of inquiry-based learning in a developmental biology course. *CBE—Life Sciences Education*, *7*(1), 54–63. doi: 10.1187/cbe.07-10-0091

Gormally, C., Brickman, P., Hallar, B., & Armstrong, N. (2009). Effects of inquiry-based learning on students' science literacy skills and confidence. *International Journal for the Scholarship of Teaching and Learning*, *3*(2), n2.

Hanauer, D. I., Graham, M. J., Betancur, L., Bobrownicki, A., Cresawn, S. G., Garlena, R. A., ... & Russell, D. A. (2017). An inclusive research education community (iREC): Impact of the SEA-PHAGES program on research outcomes and student learning. *Proceedings of the National Academy of Sciences USA*, *114*(51), 13531–13536.

Hanauer, D. I., Nicholes, J., Liao, F.-Y., Beasley, A., & Henter, H. (2018). Short-term research experience (SRE) in the traditional lab: Qualitative and quantitative data on outcomes. *CBE—Life Sciences Education*, *17*(4), ar64.

Heider, E. C., Valenti, D., Long, R. L., Garbou, A., Rex, M., & Harper, J. K. (2018). Quantifying sucralose in a water-treatment wetlands: Service-learning in the analytical chemistry laboratory. *Journal of Chemical Education*, *95*(4), 535–542. doi: 10.1021/acs.jchemed.7b00490

Hurtado, S., Cabrera, N. L., Lin, M. H., Arellano, L., & Espinosa, L. L. (2009). Diversifying science: Underrepresented student experiences in structured research programs. *Research in Higher Education*, *50*(2), 189–214. doi: 10.1007/s11162-008-9114-7

Jaskyte, K., Taylor, H., & Smariga, R. (2009). Student and faculty perceptions of innovative teaching. *Creativity Research Journal*, *21*(1), 111–116. doi: 10.1080/10400410802633673

Lent, R. W., Brown, S. D., & Hackett, G. (1994). Toward a unifying social cognitive theory of career and academic interest, choice, and performance. *Journal of Vocational Behavior*, *45*, 79–122.

Mader, C. M., Beck, C. W., Grillo, W. H., Hollowell, G. P., Hennington, B. S., Staub, N. L., … & White, S. L. (2017). Multi-institutional, multidisciplinary study of the impact of course-based research experiences. *Journal of Microbiology & Biology Education*, *18*(2). doi: 10.1128/jmbe.v18i2.1317

National Research Council. (1996). *National science education standards*. Washington, DC: National Academies Press.

Olimpo, J. T., Fisher, G. R., & DeChenne-Peters, S. E. (2016). Development and Evaluation of the *Tigriopus* course-based undergraduate research experience: Impacts on students' content knowledge, attitudes, and motivation in a majors introductory biology course. *CBE—Life Sciences Education*, *15*(4), ar72. doi: 10.1187/cbe.15-11-0228

Seidel, S. B., Reggi, A. L., Schinske, J. N., Burrus, L. W., & Tanner, K. D. (2015). Beyond the biology: A systematic investigation of noncontent instructor talk in an introductory biology course. *CBE—Life Sciences Education*, *14*(4), ar43. doi: 10.1187/cbe.15-03-0049

Seymour, E., Hunter, A.-B., Laursen, S. L., & DeAntoni, T. (2004). Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study. *Science Education*, *88*(4), 493–534. doi: 10.1002/sce.10131

Silverthorn, D. U. (2006). Teaching and learning in the interactive classroom. *Advances in Physiology Education*, *30*(4), 135–140. doi: 10.1152/advan.00087.2006

Spell, R. M., Miller, J. A. G. K. R., & Beck, C. W. (2014). Redefining authentic research experiences in introductory biology laboratories and barriers to their implementation. *CBE—Life Sciences Education*, *13*, 102–110.

Staub, N. L., Blumer, L. S., Beck, C. W., Delesalle, V. A., Griffin, G. D., Merritt, R. B., … & Mader, C. M. (2016). Course-based science research helps students from diverse institutions. *CUR Quarterly*, *37*, 36–46.

Theobald, E. (2018). Students are rarely independent: When, why, and how to use random effects in discipline-based education research. *CBE—Life Sciences Education*, *17*(3), rm2. doi: 10.1187/cbe.17-12-0280

Theobald, R., & Freeman, S. (2014). Is it the intervention or the students? Using linear regression to control for student characteristics in undergraduate STEM education research. *CBE—Life Sciences Education*, *13*, 41–48

Trujillo, G., & Tanner, K. D. (2014). Considering the role of affect in learning: monitoring students' self-efficacy, sense of belonging, and science identity. *CBE—Life Sciences Education*, *13*(1), 6–15. doi: 10.1187/cbe.13-12-0241

Usher, E. L., & Pajares, F. (2008). Sources of self-efficacy in school: Critical review of the literature and future directions. *Review of Educational Research*, *78*(4), 751–796. doi: 10.3102/0034654308321456

Velasco, J. B., Knedeisen, A., Xue, D., Vickrey, T. L., Abebe, M., & Stains, M. (2016). Characterizing instructional practices in the laboratory: The Laboratory Observation Protocol for Undergraduate STEM. *Journal of Chemical Education*, *93*(7), 1191–1203.

Weaver, G. C., Russell, C. B., & Wink, D. J. (2008). Inquiry-based and research-based pedagogies in undergraduate science. *Nature Chemical Biology*, *4*, 577–580.

Winkelmann, K., Baloga, M., Marcinkowski, T., Giannoulis, C., Anquandah, G., & Cohen, P. (2015). Improving students' inquiry skills and self-efficacy through research-inspired modules in the general chemistry laboratory. *Journal of Chemical Education*, *92*(2), 247–255. doi: 10.1021/ed500218d