

How Students Think about Experimental Design: Novel Conceptions Revealed by in-Class Activities

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Experimental design is a fundamental skill for scientists, but it is often not explicitly taught in large introductory biology classes. We have designed two pencil-and-paper in-class activities to increase student understanding of experimental design: an analyze activity, in which students are asked to evaluate data, and a design activity, in which students are asked to propose a novel experiment. We found that students who completed the design activity but not the analyze activity performed significantly better on the Expanded Experimental Design Ability Tool (E-EDAT) than did students who attended a didactic lecture about experimental design. By using grounded theory on student responses on the in-class activities, we have identified a novel set of accurate and inaccurate conceptions focused on two aspects of experimental design: sample size and the repetition of experiments. These findings can be used to help guide science majors through mastering the fundamental skill of designing rigorous experiments.

Keywords: experimental design, education, learning progression, active learning, large lecture

Experimental design is a fundamental skill, essential for achieving success in science (Coil et al. 2010) and gaining fluency in scientific literacy and critical thinking in general (Brewer and Smith 2011). However, explicit instruction and practice in experimental design is often lacking in introductory biology lecture courses because of perceived time pressures, large class sizes, and the need to emphasize content rather than skills (Dirks and Cunningham 2006).

Efforts have been made to develop activities to test and improve students' skills and knowledge of experimental design (Hoefnagels 2002, Hiebert 2007, White et al. 2009, Pollack 2010, Sirum and Humburg 2011, D'Costa and Schlueter 2013, Kloser et al. 2013). In addition, students' understanding of the significance of controls has been addressed in many studies (Shadmi 1981, Chen and Klahr 1999, Lin and Lehman 1999, Boudreaux et al. 2008, Shi et al. 2011). In biology, the development of a validated assessment to measure student understanding of experimental design (Sirum and Humburg 2011) illustrated how challenging it is for introductory-level college students to design well-controlled experiments. However, despite this body of

research, there are few studies in which students' accurate and inaccurate conceptions about experimental design have been identified (Kanari and Millar 2004, White et al. 2009, Colon-Berlinger and Burrows 2011). Therefore, there is a need for additional studies to investigate how best to teach this topic to introductory biology students and what aspects of experimental design are particularly difficult for students to grasp.

In this Education article, we describe two pencil-and-paper in-class group activities designed to test alternative hypotheses about how best to teach experimental design in a large introductory biology classroom. We describe the relative effectiveness of these activities in the improvement of students' experimental design ability and discuss specific accurate and inaccurate conceptions that we identified from student responses to the in-class activities. To determine whether inaccurate conceptions persist as students progress through the undergraduate biology curriculum, we have also assessed students enrolled in upper-level biology courses on their understanding of two key elements of experimental design: sample size and repeating an experiment.

Development of in-class paper-and-pencil activities focused on experimental design

Numerous studies have demonstrated that active learning approaches more effectively increase student learning than do traditional lectures (Hake 1998, Beichner et al. 2007, Freeman et al. 2007). However, there have been few studies on the relative effectiveness of different types of active learning approaches for helping students learn specific concepts (Eddy et al. 2013). Our first goal was to develop in-class activities to test alternative hypotheses for how best to teach experimental design in a large introductory biology lecture hall. On the basis of previous studies (Boudreaux et al. 2008, Crowe et al. 2008), we reasoned that student understanding of experimental design could be improved by working in a group (a) to develop a hypothesis and design an experiment to test that hypothesis (the *design* activity; see supplemental appendices A1 and A2) or (b) to analyze and draw appropriate conclusions from mock experimental data (the *analyze* activity; see supplemental appendices B1 and B2). Both tasks require higher-order thinking and are considered *high level* on Bloom's taxonomy of cognitive domains (Bloom and Krathwohl 1956); however, the first activity requires synthesis-level skills, whereas the second relies on analysis and evaluation skills.

The in-class activities were based on a nontechnical scenario approachable for students taking their first biology course. Both activities prompted the students to consider the basic elements of a well-designed experiment and were structured as a series of guided prompts (Lin and Lehman 1999). We designed both activities with the goal of improving students' ability to explain the importance of the elements included in an experimental design and to recognize the iterative nature of science and the tentative nature of results (Giere 2004). The activities were pilot tested twice with students in a large introductory biology course and revised before the final versions were administered. The data reported in this article are from the student responses to the final version of the activities.

Implementation of the activities

Students enrolled in Biology 180, the first course of a three-quarter introductory biology series at a large public research university, completed the activities on the second day of class in autumn 2011. This introductory biology course is a required gateway course for all students interested in majoring in biological sciences and is focused on the topics of ecology and evolution. Typical enrollment is approximately 600–800 students, primarily sophomores. All of the students attend the same lecture period and are asked to sit with students from their lab sections. For the in-class activity, the students self-aggregated into groups of two or three on the basis of where they were sitting in the large traditional lecture hall, and the student groups were randomly assigned one of the two activities to complete in the lecture hall. While they were working on the activity, the students could request help from other groups, the instructor, or teaching

assistants (TAs). One instructor and 16 TAs (approximately 40 students per TA) circulated around the room to answer questions while the students were working on the activities. Because these activities were administered on the second day of class, the TAs had only minimal experience facilitating group discussions, so they primarily responded to student-generated questions. Participation points were given for completing the activity, independent of performance. Approval for this study was obtained from the University of Washington Institutional Review Board (application no. 36743).

Assessment of experimental design ability

To measure the impact of the in-class activity on students' ability to design an experiment, we adapted the Experimental Design Ability Tool (EDAT; Sirum and Humburg 2011) to create the Expanded EDAT (E-EDAT). The EDAT is an open-ended response instrument administered as a pre- and posttest in which students are asked to design an investigative strategy to address a company's claim regarding one of its products (Sirum and Humburg 2011). The instrument is content independent; it works particularly well for introductory biology students and nonmajors, because it does not require any technical expertise. However, in our initial administration of the EDAT, we found that several of the grading criteria did not discriminate among our students. To enhance the discrimination ability of the test, we created the E-EDAT by adding prompts to the EDAT that direct students to (a) design an experiment that would test a company's claim, (b) provide justification for each element of their research design, and (c) state whether the conclusions drawn from their proposed study could prove the company's claim (supplemental appendix C1).

To score the students' responses on the E-EDAT, we developed an expanded scoring rubric (supplemental appendix C2) that awarded the students points for recognizing that they needed to include an experimental design element (e.g., a large sample size) and for giving an appropriate explanation of why that element was needed (e.g., to account for natural variability in the population). We were particularly interested in their reasoning, because it had previously been shown that students often understand *what* components are important for experimental design but do not necessarily know *why* they should use them (Boudreaux et al. 2008). We did not introduce any novel elements to the E-EDAT, but through an iterative process based on student responses on the EDAT, we altered the scoring to reflect both an inclusion of essential elements and appropriate reasoning for including those elements. Whether a response warranted partial credit or full credit for a criterion on the E-EDAT was determined through an iterative process with four different raters, who scored the E-EDAT responses independently and then held norming sessions to come to agreement on what score to give a particular response. Content validity of the final rubric was affirmed by asking three experts in biology to confirm that

the scoring rubric was scientifically accurate and relevant to the understanding of experimental design. Unlike the binary system employed in the original EDAT rubric, this expanded scoring system allowed us to identify students with an intermediate understanding of a concept. The students could receive 17 points using the E-EDAT scoring rubric, as opposed to the 10 points possible on the original EDAT (Sirum and Humburg 2011).

The students completed the E-EDAT online, outside of class; the pretest was completed the evening before the in-class activity, and the posttest was completed the evening after the in-class activity. Only those students who participated in the in-class activity, completed the pre- and posttests, and consented to have their data analyzed were included in the study. From a consenting population of 357 students who completed the *design* activity and 276 students who completed the *analyze* activity, we selected a random subset of pre- and posttests to score with the expanded rubric and then included only the responses from the consenting students in the final analysis ($n = 87$ in the *design* activity group; $n = 95$ in the *analyze* activity group). All of our future references to the effectiveness of the in-class activities are based on the data from this randomly selected subset of the students' pre- and posttests. The E-EDATs were scored blindly by two independent graders. To assess the level of agreement between the graders, we calculated the interrater reliability using Cohen's kappa coefficient for a subset of blinded responses (90 responses each on the pre- and posttests) graded independently by each grader. The interrater reliability on individual questions ranged from .54 to .89, with a reliability of .76 across all of the questions. This indicates moderately strong agreement between the two graders and illustrates that the expanded scoring rubric provides sufficient guidance to achieve reliability between independent graders.

We compared the experimental design ability of students who completed the in-class activities with that of students who learned experimental design through a traditional lecture by measuring learning gains on the E-EDAT. The students in all three comparison groups (i.e., *design* activity, *analyze* activity, lecture) were enrolled in Biology 180, but the students who participated in the didactic lecture took the course in a different term and with a different instructor. The students in the traditional lecture course were assigned the same readings and received instruction of equivalent length to the in-class activities on the scientific method and experimental design. The lecture included examples of experimental data that illustrated inherent variation in a population and variable outcomes from repeating an experiment with a different population. The lecture also included explicit statements that a hypothesis can never be definitively proven (one of the elements scored on the assessment). One hundred student pre- and posttest responses were randomly selected from the lecture group and scored; we compared the lecture students' learning gains with the gains attained by the students who completed the activities.

Identification of students' accurate and inaccurate conceptions regarding experimental design

Many terms have been used to describe student conceptions, including *naive conceptions* (Strike and Posner 1992), *alternative conceptions* (Mak et al. 1999, Poehnl and Bogner 2013), *preconceptions* (Clement et al. 1989, Ryan and Aikenhead 1992), *misconceptions* (Coley and Tanner 2012, Yates and Marek 2013), and *inaccurate conceptions* (Zuckerman 1994, Edens and Potter 2003). In this article, we will use a model of describing student conceptions as either accurate or inaccurate, defining *accurate* as being in accordance with what is known to be scientifically true and confirmed by a group of expert scientists. The students' handwritten responses to questions posed on the in-class activity worksheets were transcribed and coded as accurate, inaccurate, a mixed model that was a combination of accurate and inaccurate, or too vague to determine accuracy. A response was classified as *vague* if it was incomplete, did not answer the question, or was so general that we could not determine whether the student held an inaccurate or accurate conception. We took a conservative approach in our analysis by removing vague answers from the data set so that we did not incorrectly infer what the students were thinking (Gormally et al. 2012).

We chose to focus on two aspects of experimental design that we determined were challenging for the students on the basis of their low E-EDAT scores: sample size and repeating an experiment (supplemental table S1). The majority of the students' answers on the E-EDAT did not include any mention of sample size or repetition, which may be because of the open-ended nature of the E-EDAT, which does not contain specific prompts for students to address each of these aspects of experimental design. Alternatively, it could be because the students did not think that sample size and repeating an experiment are important elements of experimental design. The commonality between these two elements is that both sample size and repeating an experiment are relevant to one's confidence in a conclusion based on a given set of data and require an understanding of the inherent variation that exists in biological populations; they both help students understand the iterative, tentative nature of scientific results.

In order to assess the quality of the students' conceptions, we analyzed their responses on the in-class worksheets, because the students were explicitly asked to consider sample size and repeating an experiment as they completed those worksheets (table 1). Grounded theory was used to identify specific conceptions—both accurate and inaccurate conceptions—that the students held about sample size and repeating an experiment from the in-class activities. *Grounded theory* is a process by which researchers do not hold previous ideas or hypotheses about the data; rather, the themes emerge from the data itself (Glaser and Strauss 1967). We decided to use this method as a way to examine the students' responses without prior bias in order to uncover potentially novel conceptions. Two raters then

Table 1. Prompts on each of the activities for sample size and repeating an experiment.

Activity	Sample size	Repeating an experiment
Design	Why did you choose that number of poppies?	Should you repeat the experiment? Why or why not?
Analyze	Why is sample size important?	Why was the experiment repeated?

scored the students' written answers on the in-class activities for the presence of these conceptions. The raters' agreement averaged 70%, and disagreement in coding was discussed to achieve consensus. To achieve expert validation, we asked a group of five expert biologists (*expert* was defined as holding a PhD in a biology-related field) in our research group to review the list of identified accurate and inaccurate conceptions (see the tables), and they agreed with the raters' designations. In addition, we asked a group of three outside expert biologists to confirm the designations.

Comparing introductory students with advanced students to determine whether inaccurate conceptions persist throughout the curriculum

We also surveyed undergraduate biology majors enrolled in 400-level (senior-level) courses ($n = 122$) to assess their understanding of the importance of sample size and repeating an experiment and to investigate whether they maintained the inaccurate conceptions held by the introductory students. Using an online survey, the advanced students were asked a subset of the questions from the *analyze* activity, because the question prompts were more direct and elicited fewer vague conceptions than did the question prompts of the *design* activity. These students received participation points for completing the questions regardless of the accuracy of their responses. The same two independent raters who coded the introductory student responses coded the advanced student responses, using the same set of categories described for the introductory students. Rater agreement was established to be over 70%, and disagreements in coding were discussed to achieve consensus.

Statistical analysis

As a preliminary analysis, Student's *t*-tests were used to compare the students' gain scores on the E-EDAT among the three groups: the students who completed the *design* activity, the students who completed the *analyze* activity, and the students who were in the lecture course. The gains were calculated as the posttest score minus the pretest score. However, there are some differences in the characteristics of the students in the three groups (see table 2) that may be correlated with the test score gains. To control for these differences, we used a multiple linear regression model in which each student's test score gain was the response variable, and observable student characteristics, including gender, ethnicity, socioeconomic status, grade point average, and verbal SAT score, serve as predictor variables. This regression model produces estimates of two treatment effects: the treatment

effect of the *design* activity relative to the lecture and the treatment effect of the *analyze* activity relative to the lecture. In each case, the treatment effect is the average difference in test score gains between the two groups, holding observable characteristics of students in the two groups constant.

In order to determine significant differences in the student conceptions derived from grounded theory, a chi-squared analysis was used to compare the inaccurate, mixed model, and accurate conceptions, and *t*-tests were used for comparing the specific student conceptions ($\alpha = .05$).

Finding 1: An active approach leads to greater understanding of experimental design than passive lecturing does. The introductory biology students showed gains in their ability to design an experiment after the in-class pencil-and-paper activities, independent of the type of activity, and the students who completed the design activity had significantly higher gains than did the students who attended a didactic lecture.

We found that the students who completed the *design* and the students who completed the *analyze* activity had similar learning gains when their pre- and posttests were compared ($p = .21$). However, only the students who completed the *design* activity demonstrated significantly higher gains on the E-EDAT than the group of students who learned about experimental design through the didactic lecture (*t*-test, $p < .05$; figure 1). The average score on the posttest for all of the groups was 7.6 out of 17, with no individual group scoring higher than 8.1, which indicated no ceiling effect (table S1). The learning gains could be seen in multiple criteria (table S1) and could not be attributed to one particular aspect of the E-EDAT.

The results of the linear regression model used to control for differences in the observable characteristics of the students in the three groups (table 2) indicate that, holding individual student characteristics constant, the students who completed the *design* experiment gained almost half a point more out of 17 possible points, on average, than did the students in the lecture class, so the differences in the E-EDAT scores are likely due to the differences in activities, not to differences in the student population ($p = .022$; table 3). The observation that the students in the lecture group did not show gains from the pretest to the posttest indicates that the process of taking the E-EDAT itself did not lead to learning.

To account for the possibility that the variability in test scores may have differed among the three groups, we used Cohen's *d* to calculate a standardized effect size for each group, which expresses the difference between groups in units of standard deviations. With pretest–posttest data, it is appropriate to use a modification of Cohen's *d* that accounts

Table 2. Demographic information for the subset of students who completed the activities or experienced a didactic lecture and whose scores were analyzed.

	Design (n = 87)	Analyze (n = 95)	Lecture (n = 100)
Grade point average	3.36*	3.28	3.23
SAT verbal score	609	593	585
Low socioeconomic status ^a (percentage of the respondents, %)	8.0*	12.6	19.0
Racial or ethnic identity (%)			
African American	2.3	4.2	2.0
American Indian	1.1	0.0	3.0
Asian	33.3	34.7	39.0
White	51.7	43.2	37.0
Hawaiian or Pacific Islander	1.1	1.1	2.0
Hispanic	2.3	2.1	5.0
International	5.7	9.5	8.0
No race information	2.3	5.3	4.0
Female (%)	63.2	62.1	66.0

^aLow socioeconomic status was measured by admission into the Equal Opportunity Program. * $p < .05$.

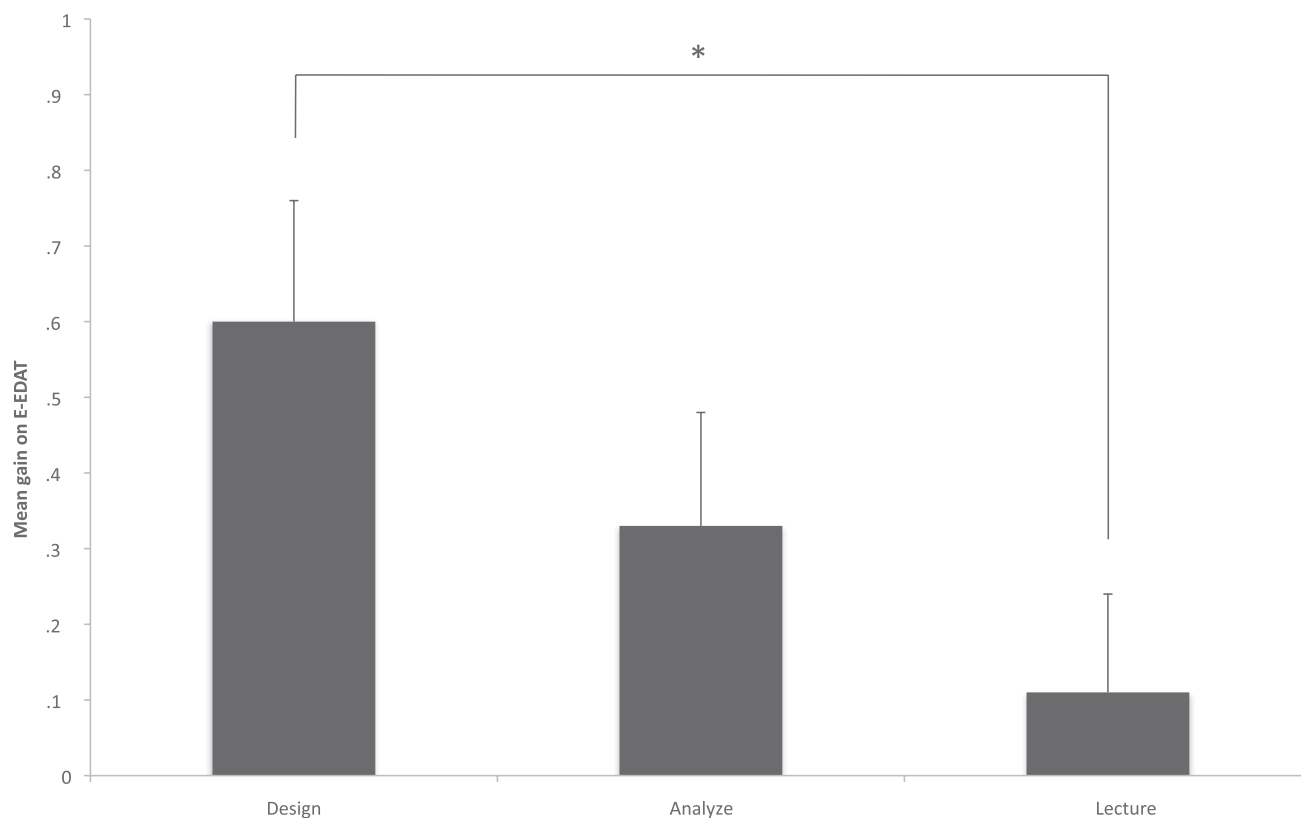


Figure 1. Students who completed the design activity scored higher on the Expanded Experimental Design Ability Tool (E-EDAT) than did students who experienced only a lecture on experimental design (design activity, $n = 87$; analyze activity, $n = 95$; lecture, $n = 100$; design–analyze comparison, $p = .210$; design–lecture comparison, $p = .018$; analyze–lecture comparison, $p = .275$). The gain was calculated as the posttest score minus the pretest score. The error bars represent the standard error.

Table 3. Multiple linear regression of gain scores against individual student characteristics.

Variable correlated with gain score	Coefficient	Standard error	t	p
Intercept	.050	0.831	0.060	.952
Grade point average	-.016	0.223	-0.071	.944
SAT verbal score	.000	0.001	-0.127	.899
Underrepresented minority	.441	0.396	1.112	.267
Low socioeconomic status	-.265	0.334	-0.793	.429
Female	.284	0.182	1.563	.119
<i>Design</i> group	.498	0.217	2.298	.022*
<i>Analyze</i> group	.248	0.211	1.175	.241

**p* < .05.

for the same students' being tested twice (Andrews et al. 2011). Therefore, we calculate the effect size for each group as

$$d = \frac{\bar{X}_{\text{post}} - \bar{X}_{\text{pre}}}{s_g / \sqrt{2(1-r)}}$$

where \bar{X}_{post} and \bar{X}_{pre} are the average scores on the posttest and pretest, respectively; s_g is the standard deviation of the raw gain scores; and r is the correlation between student scores on the pre- and posttests. The effect size was .367 in the *design* group, .209 in the *analyze* group, and .055 in the lecture group.

Finding 2: Introductory students do not have a strong understanding of the importance of sample size and repeating an experiment. The analysis of the introductory students' written responses on the in-class activity worksheets revealed that the students harbored three distinct levels of understanding about sample size and repeating an experiment: accurate, inaccurate, and a combination of accurate and inaccurate conceptions (figure 2a, 2b). If we combine the student responses that were completely inaccurate with those that contained mixed conceptions, we see that the majority of the student responses on the *design* activity and the *analyze* activity contained some inaccurate conceptions about both sample size (*design*, 75.2%; *analyze*, 69.8%) and repeating an experiment (*design*, 63.4%; *analyze*, 81.1%). The students' responses revealed more inaccurate conceptions surrounding the purpose of repeating an experiment than regarding the importance of sample size for both the *design* (45.5%) and the *analyze* (52.2%) activities (*t*-test, $p < .01$). Interestingly, the *design* activity responses contained significantly fewer inaccurate conceptions about sample size than did the *analyze* activity responses (10.2% and 39.6%, respectively; *t*-test, $p < .01$).

Notably, there were significantly more vague answers to the question about sample size in the *design* activity (47.3%) than in the *analyze* activity (12.7%) (data not shown).

However, when students were prompted to provide reasoning for repeating an experiment, their responses contained similar percentages of vague responses in both activities (*design*, 11.8%; *analyze*, 17.4%). Vague responses may reflect confused thinking, a misinterpretation of the question, or a low level of motivation to answer the question.

Finding 3: Novel accurate conceptions and inaccurate conceptions were identified from introductory student responses for sample size and repeating an experiment on the in-class activities. In order to further explore what conceptions the students held about sample size and repeating an experiment, we used grounded theory to identify three distinct accurate conceptions (table 4a) and three distinct inaccurate conceptions (table 4b) about sample size. We also identified three distinct accurate conceptions (table 5a) and seven distinct inaccurate conceptions (table 5b) about repeating an experiment. Several students who completed the *design* activity (8.9%) stated that it was not necessary to repeat an experiment, particularly if the sample size was large enough. Because the *analyze* activity did not allow the students this option, we cannot conclude whether this idea is a general inaccurate conception held by introductory students or whether the nature of the *design* exercise led the students to this conception.

Finding 4: Some inaccurate conceptions are "sticky." The advanced students held fewer inaccurate and more accurate conceptions than did the introductory students who completed the *analyze* activity, but over a third of the advanced students continued to harbor inaccurate conceptions.

We surveyed the advanced biology majors' understanding of experimental design by asking them the same questions about sample size and repeating an experiment that were included in the *analyze* activity. We found that the advanced students held significantly more accurate conceptions (advanced, 57.3%; introductory, 30.2%) and fewer inaccurate conceptions about sample size (advanced, 14.5%;

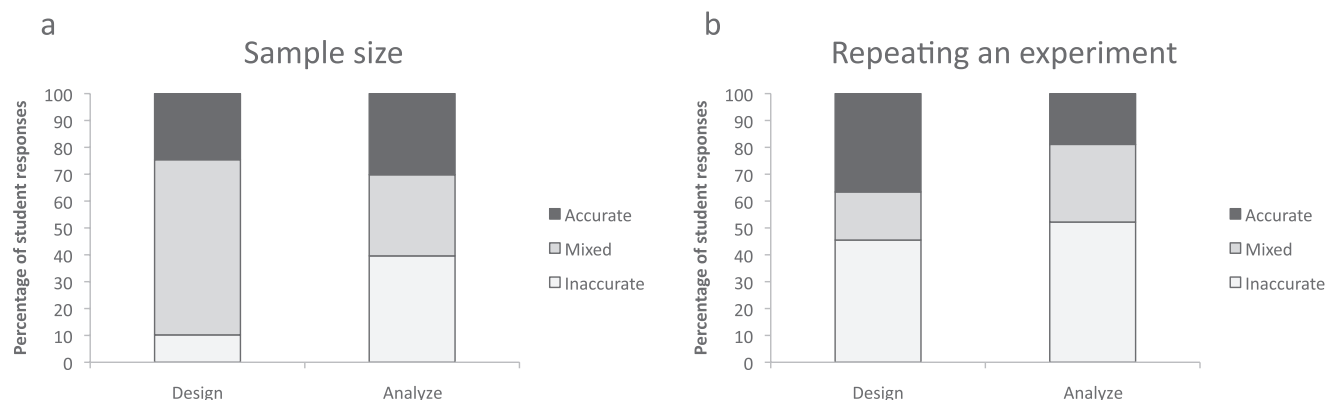


Figure 2. Introductory students' conceptions of (a) sample size and (b) repeating an experiment. For responses regarding the rationale for sample size, the data are shown as percentages of the total number of student group responses ($n = 69$ for the design group, $n = 96$ for the analyze group). The student group responses for the design activity were completely inaccurate (10.2%), completely accurate (24.6%), or a mix of accurate and inaccurate (65.2%) conceptions; the differences between these groups are statistically significant (chi-squared analysis, $p < .001$). The student group responses for the analyze activity were completely inaccurate (39.6%), completely accurate (30.2%), or a mix of accurate and inaccurate (30.2%). Chi-squared analysis indicates that these differences are not statistically significant. The student responses that were too vague to code have been removed. There was a statistically significant difference between the design and analyze student responses for inaccurate and mixed conceptions (Student's t -test, $p < .01$). For responses regarding the rationale for repeating an experiment, the data are shown as percentages of the total number of student responses ($n = 112$ for the design group and $n = 90$ for the analyze group). The student responses for the design activity were completely inaccurate (45.5%), completely accurate (36.6%), or a mix of accurate and inaccurate (17.9%). The student responses for the analyze activity were completely inaccurate (52.2%), completely accurate (18.9%), or a mix of accurate and inaccurate (28.9%). Chi-squared analysis for both the design and the analyze groups indicates that these are statistically significant differences ($p < .001$).

Table 4a. Introductory students' accurate conceptions about sample size.

Category of accurate conceptions	Example student response	Design activity	Analyze activity
It is better to have a larger sample size than a smaller one	"Large enough sample size to draw conclusion from"	82.6	53.1*
Too big of a sample size is not cost effective or manageable	"Large enough, but not terribly difficult to organize/take care of"	30.4	2.1*
A large sample size is needed because of inherent variation in a given population	"Sample size should be large in order to average out natural variation in a population"	11.6	10.4

Note: The data are shown as percentages of the number of student responses on each in-class activity ($n = 69$ for the design group, $n = 96$ for the analyze group). Student responses that were too vague to code have been removed. * $p < .05$ (Student's t -test).

introductory 39.6%) than did the introductory students who completed the *analyze* activity ($ps < .05$; figure 3). Similarly, in describing their reasoning for repeating an experiment, the advanced students held significantly more accurate conceptions (advanced, 56.1%; introductory, 18.9%) and fewer inaccurate conceptions (advanced, 9.6%; introductory, 52.2%) than did the introductory students ($ps < .05$).

When we combine the student responses that were completely inaccurate with those containing mixed conceptions, we see that the majority of responses from the advanced students contained accurate conceptions about both sample size (57.3%) and repeating an experiment (56.1%). However, we still identified a notable percentage of

inaccurate conceptions in the advanced students' responses (42.7% for sample size, 43.8% for repeating an experiment), which indicate that these conceptions about experimental design persist even among students who have almost completed the undergraduate biology curriculum.

We found that the advanced students held more accurate conceptions (table 6a) and fewer inaccurate conceptions (table 6b) about sample size than did their introductory-level counterparts. Specifically, significantly more advanced student responses (77.3%) than introductory student responses (53.1%) exhibited the accurate conception that a larger sample size is good ($p < .05$; table 6a). However, there was no significant difference in the advanced and introductory

Table 4b. Introductory students' inaccurate conceptions about sample size.

Category of inaccurate conceptions	Why the conception is incorrect	Example student response	Design activity	Analyze activity
Larger sample size ensures randomized or controlled results	A large sample size can still be biased if only certain individuals are chosen (e.g., sampling error)	"Large sample size—randomization"	11.6	16.7
A larger sample size gives more accurate data	A larger sample size may yield a more accurate interpretation of the data but not necessarily more accurate data if the data collected are all outliers (e.g., sampling error)	"Larger sample size, more accurate data"	26.1	15.6
A larger sample size eliminates variables, chance, or outliers	A larger sample size can decrease the impact of variables and outliers but does not decrease their number	"It's a large sample size to decrease unusual data"	37.7	38.5

Note: The data are shown as percentages of the number of student responses on each in-class activity ($n = 69$ for the *design* group, $n = 96$ for the *analyze* group). Student responses that were too vague to code have been removed. * $p < .05$.

Table 5a. Introductory students' accurate conceptions about repeating an experiment.

Category of accurate conceptions	Example student response	Design activity	Analyze activity
Repeating an experiment increases confidence in the data	"Yes, more trials will show that the experiment is replicable"	35.7	43.3
Repetition reduces the likelihood that uncontrolled variable affected the results	"Yes, to account for uncontrolled variables (such as animals and insects)"	7.1	3.3
Repetition reduces the impact of chance or randomness on the interpretations	"To verify that nothing happened by accident to change the outcome"	10.7	6.7
Repetition is needed because of inherent variation in a given population	"Some poppy seeds might not be from the same gene pool"	0.9	0

Note: The data are shown as percentages of the number of student responses on each in-class activity ($n = 112$ for the *design* group, $n = 90$ for the *analyze* group). Student responses that were too vague to code have been removed. * $p < .05$.

Table 5b. Introductory students' inaccurate conceptions about repeating an experiment.

Category of inaccurate conceptions	Why the conception is incorrect	Example student response	Design activity	Analyze activity
It is not necessary to repeat an experiment	Experiments need to be repeated	"No, the sample size should account for any differences"	8.9*	—
Repeat to increase sample size	Repeating an experiment gives a replicate, not a larger sample size	"Repeated to create a larger sample size"	9.8	12.2
Repeat to change a variable	When repeating an experiment, all variables should remain constant	"To see how results will vary with diff[erent] variables"	5.4	6.7
Repeat only to avoid making errors	This is not the only reason one would repeat an experiment	"Repeated to reduce effects of making mistakes"	8.0	10.0
Repeat to eliminate outliers, chance, or variation	Repeating an experiment can decrease the impact of variables and outliers but does not decrease their number	"To eliminate the possibility of an anomaly"	17.0	22.2
Repeat to make data—not the interpretation—more accurate	Repeating an experiment may give a more accurate interpretation of the data but not necessarily more accurate data if there were an uncontrolled variable affecting the accuracy	"To make the results more accurate"	17.9	28.9
Repeat to make certain or prove that the findings are correct (overstating the claim of what a repeated experiment could tell them)	Too absolute; you cannot prove a hypothesis	"To ensure the validity of the results"	18.8	28.9

Note: The data are shown as percentages of the number of student responses on each in-class activity ($n = 112$ for the *design* group, $n = 90$ for the *analyze* group). Student responses that were too vague to code have been removed. * $p < .05$.

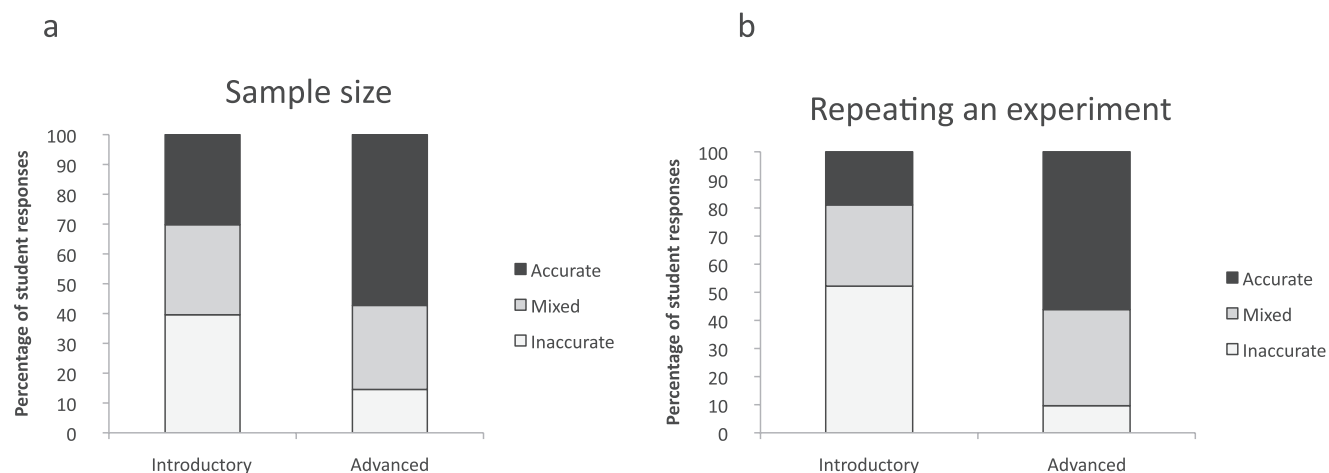


Figure 3. Advanced students' conceptions of (a) sample size and (b) repeating an experiment. For sample size, the data are shown as percentages of the total number of student responses ($n = 110$). The advanced student responses were completely inaccurate (14.5%), completely accurate (57.3%), or a mix of accurate and inaccurate (28.2%). Compared with the introductory students, who completed the analyze activity, the advanced students had significantly more accurate conceptions and fewer inaccurate conceptions (chi-squared analysis, $p < .01$). Student responses that were too vague to code have been removed. For repeating an experiment, the data are shown as percentages of the total number of student responses ($n = 114$). The advanced student responses were completely inaccurate (9.6%), completely accurate (56.1%), or a mix of accurate and inaccurate (34.2%). The advanced students had significantly more accurate conceptions than inaccurate conceptions (chi-squared analysis, $p < .01$). The introductory student group is the same as the analyze group (see figure 2).

Table 6a. Advanced students' accurate conceptions about sample size.

Category of accurate conceptions	Percentage of responses
A larger sample size is good	77.3*
Too big of a sample size is not cost effective or manageable	3.6
A large sample size is needed because of inherent variation in a given population	20.0

Note: The data are shown as percentages of the total number of advanced student responses ($n = 110$). Student responses that were too vague to code have been removed. The advanced student responses were compared (using Student's *t*-tests) with the introductory student group responses on the *analyze* activity (see table 3a). * $p < .05$.

Table 6b. Advanced students' inaccurate conceptions about sample size.

Category of inaccurate conceptions	Percentage of responses
Larger sample size gives randomized or controlled results	2.7*
A larger sample size gives more accurate data	31.8*
A larger sample size eliminates variables, chance, or outliers	4.5*

Note: The data are shown as percentages of the total number of advanced student responses ($n = 110$; see table 3a). Student responses that were too vague to code have been removed. The advanced student responses were compared (using Student's *t*-tests) with the introductory student group responses on the *analyze* activity (see table 3a). * $p < .05$.

students' recognition that too big of a sample size is not cost effective (advanced, 3.6%; introductory, 2.1%). Importantly, we did not observe a statistically significant difference between the advanced and introductory students' recognition that sample size is important because of inherent natural

biological diversity (advanced, 20%; introductory, 10.4%), the primary reason that most biologists would give for including a large sample size.

In general, the advanced students held fewer inaccurate conceptions about sample size than did the introductory

Table 7a. Advanced students' accurate conceptions about repeating an experiment.

Category of accurate conceptions	Advanced students
Reproducibility increases confidence in data	52.6
Reduce likelihood that uncontrolled variable affected results	21.9*
Reduce impact of chance or randomness on interpretations	36.8*

Note: The data are shown as percentages of the total number of advanced student responses ($n = 114$; see table 4a). Student responses that were too vague to code have been removed. The advanced student responses were compared (using Student's t -tests) with the introductory student group responses on the *analyze* activity (table 4a). * $p < .05$.

Table 7b. Advanced students' inaccurate conceptions about repeating an experiment.

Category of inaccurate conceptions	Advanced students
Repeat an experiment to increase sample size	10.5
Repeat to change a variable	1.8
Repeat to avoid making errors	9.6
Repeat to eliminate outliers, chance, or variation	0.9*
Repeat to make data more accurate	14.9*
Repeat to make certain that findings are correct	13.2*

Note: The data are shown as percentages of the number of advanced student responses ($n = 114$; see table 4b). Student responses that were too vague to code have been removed. The advanced student responses were compared (using Student's t -tests) with the introductory student group responses on the *analyze* activity (table 4a). * $p < .05$.

students (table 6b); however, the inaccurate idea that a larger sample size gives more accurate data was more common in the advanced group (advanced, 31.8%; introductory, 15.6%).

The advanced students held more accurate conceptions and fewer inaccurate conceptions than did the introductory students (table 7a, 7b) regarding the importance of repeating an experiment. A significantly higher percentage of the advanced students correctly stated that it is important to repeat an experiment to reduce the likelihood that an uncontrolled variable has affected the results (advanced, 21.9%; introductory, 3.3%) or to reduce the impact of chance or randomness on the interpretation of the results (advanced, 36.8%; introductory, 6.7%; $ps < .05$). However, the advanced students and the introductory students were equally likely to recognize that repeating an experiment and getting a reproducible result would increase confidence in the data (advanced, 52.6%; introductory, 43.3%; table 7a). Significantly fewer of the advanced students held the inaccurate conception that you repeat an experiment to eliminate outliers or to account for chance (advanced, 0.9%; introductory, 22.2%), to make the data more accurate (advanced, 14.9%; introductory, 28.9%), or to make certain that the findings are correct (advanced, 13.2%; introductory, 28.9%; $ps < .05$; table 7b).

Conclusions

We originally set out to identify which activity would lead to higher learning gains, but the finding that both in-class

activities were beneficial for improving students' experimental design ability may be even more interesting. It suggests that there may not be one "right" way to teach a skill as complex as experimental design. Because the students completed these activities in groups, we cannot disaggregate their responses by demographic characteristics for this study. However, it would be an interesting area for future research to see whether certain students learn better with an analysis or evaluation task than with a synthesis-level task.

Although we found no significant differences in E-EDAT score gains between the two activities, we did observe a difference of 0.5 point between the *design* activity and the passive lecture. Although this number is small, it is statistically significant, and we believe that it demonstrates a meaningful improvement. We were not expecting a large difference between the pre- and posttest scores for an intervention of only 30 minutes, and, given the time spent on the task, this gain is similar to what has previously been reported (Sirum and Humburg 2011).

There are at least two possible explanations for why only the *design* activity was significantly more effective than the lecture: There may be closer alignment of the design task with the assessment instrument, or the students' ability to apply concepts to new situations may increase after completing a synthesis-level activity. The development of additional validated tools to assess student understanding of experimental design would allow us to differentiate these

possibilities. The students completed either the *design* activity or the *analyze* activity in this study, but a possible area for future exploration would be to determine whether there could be a synergistic effect resulting from students completing both activities. In particular, it may be interesting to investigate whether there is an order effect, such that we see higher gains in students who complete the *analyze* activity before the *design* activity or vice versa.

We also uncovered several novel accurate and inaccurate student conceptions about experimental design. The structure of the two in-class activities probably affected which accurate and inaccurate conceptions were identified. The increased number of vague responses on the *design* activity, for example, may be a result of the more open-ended nature of the questions on that activity. Interestingly, the students in the *design* activity group were much more likely to consider the advantages of a large sample size, as well as the cost and logistical challenges associated with using a large sample size; the *design* activity was better than the *analyze* activity at eliciting these accurate conceptions concerning sample size. Furthermore, the *design* activity responses contained significantly fewer inaccurate conceptions about sample size than did the *analyze* activity responses. This suggests that the process of interpreting data may reveal more inaccuracies in students' ways of thinking than does the act of designing an experiment, which indicates that the *analyze* activity may be more effective at eliciting inaccurate student ideas. Alternatively, designing an experiment may help move students toward more accurate conceptions. Questions that prompted students to consider the purpose of repeating an experiment elicited significantly more inaccurate conceptions than did those focused on sample size. This may be because of the difficulty of the topic, the wording of the prompt, or because students are not often asked to consider why they should repeat an experiment (e.g., in "cookbook" lab courses).

Much of the research focused on gaining insight into student understanding of biological concepts has generally relied heavily on identifying student *misconceptions* (Nelson 2008), which are defined as scientifically inaccurate ideas. Although the identification of misconceptions has been valuable for the biology education community, recent findings indicate that students' misunderstandings of concepts cannot simply be described as misconceptions; rather, there is a continuum of student understanding known as a *learning progression* (Alonzo and Gotwals 2012). Learning progressions are research-based models of how core ideas are formed over time, often focused on students' ways of thinking (Songer et al. 2009, Duncan and Rivet 2013). Learners develop their understanding of complex biological concepts in stages that build on each other. It has been shown that scientifically inaccurate answers may be useful for students at early stages of learning, allowing them to partially understand a topic (Duncan and Rivet 2013). Although there are a few studies in which inaccurate but possibly productive student conceptions related to experimental design have been identified (Kanari and Millar 2004, White et al. 2009,

Colon-Berlinger and Burrows 2011), we currently lack a learning progression for undergraduate biology majors' understanding of experimental design, and we hope that findings from our study can help move the field toward this goal.

Specifically, our investigation of the differences between introductory and advanced students could be useful for developing a learning progression. Overall, the advanced students held significantly more accurate conceptions and fewer inaccurate conceptions for sample size and repeating an experiment than did the introductory students. There are a few surprising observations about the differences between the advanced and introductory students' ideas concerning the significance of sample size and repeating an experiment. First, the advanced students were more likely to hold the inaccurate conception that repeating an experiment leads to more accurate data. A possible reason for this is that the advanced students were actually thinking correctly about how repeating an experiment could lead to a more accurate interpretation of the results but simply used the phrase "more accurate data" to convey the idea that repeating an experiment will lead to increased confidence in one's interpretation of the data. This difference in language, although it is subtle, is important but may not be clear to these students. Intriguingly, this inaccurate idea of "more accurate data" could be viewed as a productive misunderstanding in a student learning progression of experimental design (Duncan and Rivet 2013). As students move from not thinking about how sample size affects the quality of the data to thinking that a larger sample size often leads to a more accurate interpretation of those data, perhaps thinking incorrectly about accurate data is an indication that the students are on the path to building a deeper understanding.

Although the advanced students were more likely to provide accurate justifications for experimental design elements, we think that it may be primarily because of an increased proficiency with statistics and may not be reflective of improved understanding of how biological variation influences experimental design. The vast majority of the introductory and advanced students who mentioned anything related to variation discussed "unique individuals" or "mutants," as opposed to the variation that exists on a natural continuum (data not shown). Although we do not have an explanation for why these biology students' did not think about inherent variation in a population, our study suggests that this concept may need to be more explicitly taught in the biology classroom.

Although it does not provide a complete picture, this study is an important first step toward revealing the types of conceptions that students hold about experimental design. The underlying reasons for which students hold these inaccurate conceptions remain to be explored. Is it a result of how we teach experimental design in lab courses—with a very small sample size and typically never repeating experiments? Do students not understand inherent variability in the population because we often present the data as averages,

and undergraduate students rarely see raw data? Do students understand the underlying biological principles but have linguistic difficulties describing precise aspects of experimental design (e.g., the difference between “decreasing the effect of outliers” and “decreasing outliers”) that make their responses inaccurate? Future directions for this research include developing research tools that target these specific inaccurate conceptions and using think-alouds and interviews to more deeply probe student understanding.

It is possible that the present results underrepresent the extent to which students hold inaccurate conceptions about experimental design. We relied on the students to come up with an inaccurate conception, as opposed to asking a specific question about the inaccurate conception, so it is possible that some of the students may have had inaccurate conceptions that they did not write down. The students also worked in groups, so they had the opportunity to discuss their responses with each other. They were able to ask the TAs and the instructor questions about the activities during the class session, so, perhaps, some of their inaccurate conceptions were clarified in class. Although our work is an important first exploration into possible conceptions that students may harbor, more work needs to be done to determine how prevalent these conceptions are for undergraduates.

There are a few limitations to this study that necessitate caution in generalizing the results. First, different instructors taught the lecture course and the course in which the activities were administered, so an instructor effect could have affected the difference we saw between the *design* activity and lecture students on the E-EDAT. Next, we collected data from the introductory students through in-class, handwritten worksheets, whereas we collected data from the advanced students through online questions. The questions were identical, but the method of delivery was different, which could have influenced the results. Finally, although we anticipate that we would obtain similar results with a different population of students, especially because we controlled for student ability in our regression model, collecting only one set of data is a limitation but is not uncommon for educational research. Determining the impact of these activities in different student populations is an interest of ours, and we encourage others to use our activities and the E-EDAT to see whether they obtain similar gains in different contexts.

In this article, we have presented two in-class activities that instructors can use to teach experimental design, a modified EDAT (E-EDAT), and a rubric to assess students' ability to design an experiment and justify their reasoning. This study also provides novel insight into how students think about specific elements of experimental design, which could be the basis for building a learning progression of undergraduate thinking about experimental design. Much work still needs to be done before we can begin to model what the learning progression may be, but we believe that

this study is an important step in our own learning progression of understanding student thinking about experimental design.

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