Guided Questions: A strategy to promote more effective and independent student experimental design in inquiry labs

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Abstract: Instructors are often challenged by the amount of student-teacher interaction required to guide students in inquiry labs. We investigated whether written inquiry prompts were equally effective in aiding students in experimental design as compared to verbal prompts. We assessed students' written assignments and survey responses to determine the usefulness of these materials. We developed a rubric that measures experimental design quality that may be useful in other laboratories to guide students in designing experiments.

Introduction

There are many successful models of inquiry laboratory instruction. Sundberg & Moncada (1994) describe several alternatives to the traditional, didactic, "cookbook" type laboratories where students are told what to do and learn. One of these is the "inquiry" lab, which they define as a laboratory activity in which the instructor leads students to discover a specific concept after being prompted by a basic question or problem (Uno & Bybee, 1994). They compare this to "open-inductive" investigation where students design and conduct their own experiments without prompts from the instructor. Our labs combine both these elements, which we refer to as "guided inquiry" because the instructor poses an initial problem, and then through active questioning, guides students in planning experiments that will help them arrive at a solution to the question (Magnusson, 1999). This approach provides more guidance to students who may be poorly prepared to tackle inquiry problems without prompts and instruction because of lack of experience, knowledge, or because they have not reached the cognitive development required for abstract thought (Lawson, 1980; Purser & Renner, 1983). A guided approach using questions should provide that instruction and therefore lower student frustration levels while still maintaining the level of intellectual challenge (Igelsrud & Leonard, 1988).

Providing adequate levels of guidance is a major challenge to instructors using inquiry (Furtak, 2006). Brief discussion and questioning by the instructor often facilitates student thinking when designing experiments (T. Crawford et al., 2000; Roth, 1996). In a lab setting with nearly twenty students, however, this important interaction can be compromised by the higher student: instructor ratio. In our experience, students become dependent on guidance from the instructor, which becomes a limiting factor affecting laboratory time constraints. Moreover, few novice teachers are confident using instructional strategies like questioning to help students grapple with deciding how to approach their scientific investigations or how to think through the predicted outcomes beforehand (B. A. Crawford, 1999). This is even more evident at the college level where instructors have had little pedagogical training (Mervis, 2001). Identifying exemplary instructional strategies should make a significant impact on how instructors are trained in these methodologies (Rushin et al., 1997).

Methods

Context of study

The laboratory materials described in this study were developed for a non-science major introductory biology class that is taken by university undergraduates to fulfill their life sciences general education requirement. The course meets two consecutive hours per week in small sections of 20 students. The labs are taught by 12-13 teaching assistants (TAs) who each teach 3 lab sections; 30-60% of TAs return each semester. Of the students who take the course, over 60% are women and approximately 15% are minorities. The students described in this study were enrolled in the course during the Spring semester of 2006. During the spring semester of 2006, the student study participants did not vary significantly demographically (gender ratio; year in school; % minority) between the treatment and control groups (Figures 1, 2, 3).

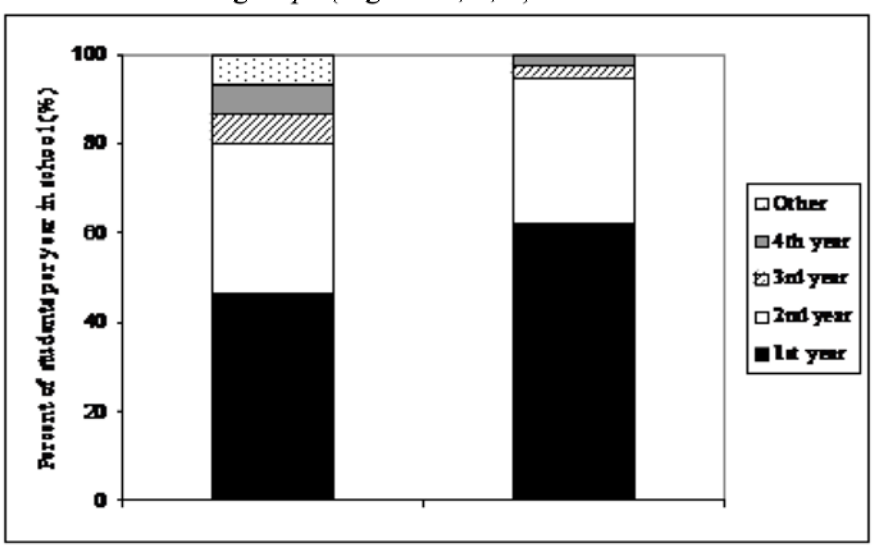

Figure 1. Distribution of students by year in school did not differ between treatment group (left) and control group (right). “Other” includes post-baccalaureate students, as well as fifth year students.

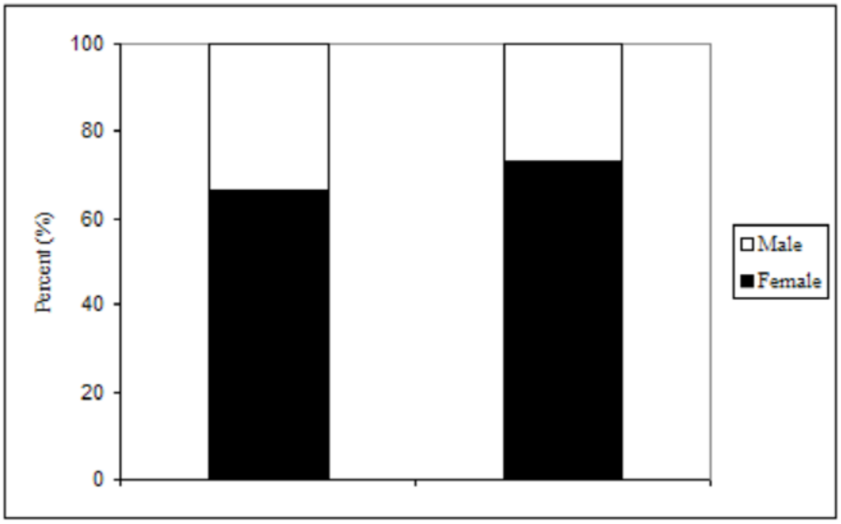

Figure 2. Female: male ratio did not differ between treatment group (shown on left) and control group. The majority of students in our inquiry labs are women.

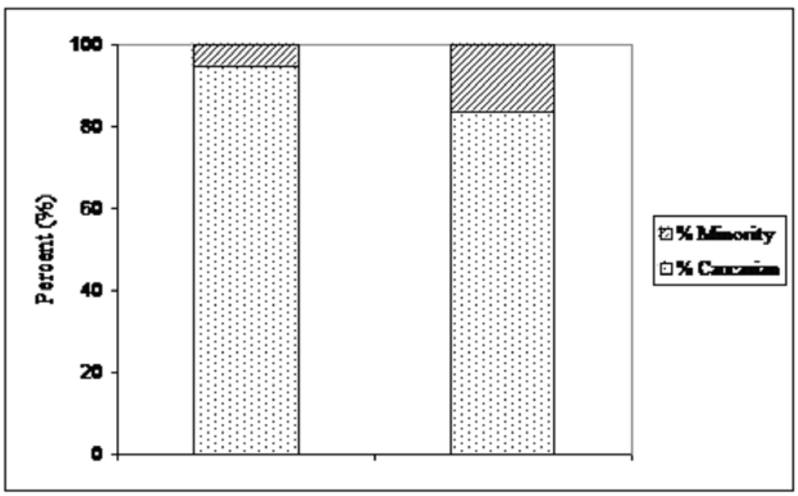

Figure 3. Treatment group (left) and control group (right) did not vary significantly in terms of percentage of minority students.

To better focus on process of science skills, the labs these students performed involved less step-by-step instructions and instead challenged the students to solve a particular problem though open-ended observation followed by opportunities for making and then testing their predictions. Working in groups of three or four, students set up and carried out their own investigations that last more than one class period. Typically, lab sequences lasted for two or three consecutive weeks. Students documented their thought processes in writing throughout the experimental phase and completed written final reports using a modification of the Science Writing Heuristic template (Keys et al., 1999) which was the primary form of assessment in our labs. The benefit of these “writing to learn” methods stems from their ability to help students organize and analyze their thought processes in a way that encourages transfer of knowledge (McCrindle & Christensen, 1995).

Guided questions

We reasoned that written inquiry prompts could adequately substitute for some of the time-consuming and challenging (yet effective) verbal questioning from an instructor, as well as fostering increased group participation and productive student discussion, effectively shifting the primary responsibility for thinking and learning from the instructor to the students. This motivated us to create a series of questions that mimic the ideal form of questioning that an experienced instructor would employ when helping students to think through a scientific investigation. Essentially, the guided questions (Box 1) are series of questions based on ideas and concepts that experienced scientists would consider when designing an experiment to achieve a certain objective. The questions were not formulated to have right or wrong answers. The students that were provided with the questions were encouraged to use the questions in any way that was helpful to them, including reading and discussing the questions in groups, or reading and answering the questions in writing on their own, or choosing not to use the questions. This study was undertaken to determine whether students who are provided written inquiry prompts (treatment group) would have increased facility in designing experiments, evidencing greater comprehension of experimental objectives and procedures, as compared to students who were provided only verbal prompts (control group).

Genetics Inquiry Lab Assignment: During this three-week lab exercise students test their understanding of inheritance by developing a series of genetics crosses to help them uncover the genotype of a C. elegans population with self-fertilizing hermaphrodites and males both carrying a recessive mutation but with an outwardly normal phenotype.

1. If you placed a single hermaphrodite together with 6 males on a mating plate with a small disc-shaped lawn of bacteria, what would the phenotype and sex of the offspring be?
2. Why would you want to cross your mystery mutant with a male instead of just allowing the hermaphrodite to self-fertilize? What would you predict would be the result of each cross?
3. How do you determine how many worms (# hermaphrodites and # males) should be placed on each plate? Would you expect successful mating 100% of the time? Would it be better to have many males and one hermaphrodite or many hermaphrodites and one male on a plate?
4. If you placed a single virgin hermaphrodite (L4 or earlier) on a small seeded plate, what would the phenotype and sex of the offspring be and how could you determine the genotype of the parents?
5. If you are performing a mating, state how you would tell if the mating worked, and what the results would look like if the gene for the trait were on an autosome, on the X-chromosome, or incompletely dominant.

Box 1. Examples of guided questions used for genetics inquiry lab assignment.

Experimental design

In order to determine whether students found the guided questions to be useful as well as to determine whether the questions had a positive impact on our students' ability to design experiments, we compared student writing from three lab sections during the spring semester of 2006. The guided questions were provided to two lab sections (n=37 students), in addition to the inquiry based lab material, while one other lab section (n=15 students) received only the inquiry based lab material which contained the lab objective and limited lab background.

The particular lab sequence in which we conducted our experiment continues over three weeks. The objective of the students' experiments is to design genetic crosses to determine the genotype of a mystery mutant *C. elegans*. Students write in-class experimental designs for three weeks, as well as a draft of a paper and a final paper. Students are permitted to discuss their experimental designs in groups, but they were each responsible for writing an experimental design in their own words, before conducting the experiment as a group. Students were given detailed guidelines for both the draft and the final paper but not for the experimental design. The students peer reviewed three other student paper drafts anonymously using an online program called Calibrated Peer Review (CPR). The program randomly assigns each student papers to peer review after the student has completed a three calibration essays. Students may have been randomly assigned to peer review students' work from either the experimental treatment or control group.

We analyzed student writing to determine whether the guided questions affected students' work. We hypothesized that the writing of students who used the guided questions would show evidence of greater understanding of the experimental procedure and purpose, indicated by greater detail and explanation expressed in their writing. Labs had run for nine weeks by the time we conducted our experiment. Prior to conducting our study, we determined that treatment and control group averages, for both lecture grade and lab grade, were not significantly different between lab classes or treatment groups.

Assessment of student writing

We used content analysis to analyze students' in-class written experimental designs. Content analysis is a systematic procedure used to examine the content of recorded human information or communications (Babbie, 2004). Content analysis involves creating a coding system about the content of an ideal experimental design, which we used as a means to objectively and quantitatively evaluate students' written work. Coding is the process by which the written content or data is classified according to a predetermined written framework, known as a codebook. For each coding question, we coded either yes or no in response to the presence or absence of written content related to the coding question (Box 2). Students' paper drafts and final papers were not analyzed with content analysis, but were graded according to a rubric based on a modification of the Science Writing Heuristic template (Keys *et al.*, 1999).

We have turned this codebook into a general experimental design rubric for students to use to help them to write their experimental designs (Box 3). Using the rubric, students can check to be sure that they have included adequate and appropriate content necessary for a good experimental design.

Coding question
Objective
1. Is an objective stated?
2. If yes to 1: Does the student write detailed information about the potential inheritance pattern of the genotype of the mystery mutant?
Background
3. Does the student state that they looked at the worms or that observations of the worms were made prior to experimenting?
4. If yes to 3: Did the student record the name of the known mutant that their mystery mutant resembles?
5. If yes to 3: Did the student describe the phenotype of the group's mystery mutant?
6. If yes to 3: Did the student describe the phenotype of the group's mystery mutant?
7. If yes to 3: Did the student write about distinguishing between various lifestages of worms?
8. If yes to 3: Did the student write that they distinguished between males and hermaphrodites?
9. If yes to 3: Did the student describe the physical and/or behavioral differences that they used to distinguish between males and hermaphrodites?
10. If yes to 3 and if this is Experimental Design Lab 11 or 12: Did the student write about distinguishing between offspring phenotypes?
Methods
11. Does the student state that worms were transferred or placed in petri dishes?
12. If yes to 11: Does the student describe the sterile procedure needed to transfer the worms from plate to plate?
13. Does the student explain the purpose of each plate that was set up—what each possible pattern of inheritance the plate is testing?
14. Does the student indicate whether the plate was self- or cross-fertilized?
15. Does the student indicate the gender of the worms transferred to each plate?
16. Does the student indicate the lifestage of any hermaphrodite worms used (L1-L4)?
17. If the student placed multiple male worms in a dish, does the student offer an explanation for this?
Analysis & Interpretation of Results
18. Does the student indicate that the results will be analyzed by observing offspring?
19. Does the student indicate that the results will be analyzed by counting phenotypic ratios for the offspring?
20. Does the student describe the potential phenotypes of the offspring?
21. Does the student describe the potential phenotypes of the offspring?
22. Does the student include Punnett squares or predicted phenotypic ratios for the predicted results?
23. Does the student explain what each result might indicate about the pattern of inheritance?

Box 2. Content analysis codebook used to analyze the quality of students' experimental designs.

Experimental Design Rubric

Use the following guidelines to write up the experiment your group proposes to carry out.

- ✓ *Context*: Provide the observations/knowledge that helped you choose your question.
- ✓ *Question*: State what you hope to learn or conclude from your tests (either those assigned to you or those you came up with on your own.)
- ✓ *Justification*: Include relevant background information about why these tests are interesting or important.
- ✓ *Tests*: Explain how your tests will provide answers to your question; include what these tests are designed to find.
- ✓ *Detail*: Provide sufficient detail so that another classmate could replicate your methods.
- ✓ *Prediction*: What is one result you expect?
- ✓ *Claims*: Describe what you may be able to conclude as a result of your tests.
- ✓ *Evidence*: Describe how you will evaluate the information from your tests.
- ✓ *Explanation*: Explain how you will be able to use the data to conclude if your question has been answered?

Box 3. Experimental design rubric, modified from the content analysis codebook.

A statistical analysis of the content analysis results was conducted to explore potential differences of interest (PROC CORR, PROC GLM, SAS 9.1). In our statistical analysis, we sought to address two major questions: (1) were there significant differences in the quality of students' writing when provided with guided questions? and (2) what kinds of writing did the guided questions affect? While students were instructed to write their experimental designs in their own words, we expected that the quality of student writing might be correlated by student group since group collaboration does play a large role in our labs. We also considered that there might be underlying correlations between the quality of different types of writing (in-class vs. formal) and so we examined all possible correlations between different types of student writing. Lastly, we recognized that differences in demographic background might contribute to differences in student writing ability and thus writing quality. Both gender and year in school of student participants were examined, to see whether these demographic variables explained differences in student writing quality. Observations (students) that were missing data for Lab 10 and/or Lab 11 experimental designs were deleted since these students had missed lab and therefore not participated in the experiment. Three observations were deleted, leaving N=49.

Student attitude survey

In order to determine student attitudes toward writing in class experimental designs and the guided questions, as well as to reveal how students used the guided questions, we distributed surveys to the students who were given guided questions. All students were asked to be specific when answering the open-ended questions. Since each question elicited multiple answers, the responses were classified into several broader response categories that encompassed the responses. Survey questions are summarized in Table 1. We present percentages based on the proportion of total number of response categories to each question. Students sometimes reported multiple responses to each question.

Table 1. Survey questions and top three most frequent responses.

Survey questions	Most frequent responses	Percent of students
How did you and your group use the guided questions?	"Used to formulate my experimental design."	51.7%
	"Used to help me understand the objective and procedures involved in my experiment."	24.1%
	"I answered the questions."	20.7%
How did the guided questions affect your experimental design?	"Using the guided questions improved my experimental design by making it more detailed and organized."	35.7%
	"The guided questions provided a starting point for my experimental design."	28.6%
	"The guided questions helped me to better understand my experiment."	17.9%

Findings

Assessment of student writing

Since we observed differences in lab grades between genders that approached statistical significance, with women scoring higher (373.48 versus 353.36 for male students; $p>0.0715$), we were interested if this might extend to student writing quality. Analyses of variance (ANOVAs) were conducted to investigate whether demographic variables potentially affecting student writing, namely, year in school and gender, explained variation in quality of student writing. Women students' experiment designs were better written ($p>0.0535$) than men students' experimental designs when analyzed as pooled experimental design data (Lab 10 experimental design + Lab 11 experimental design). The most significant difference between genders was evident in the Lab 10 experimental design, with women scoring higher ($p>0.0091$). However, there was no significant difference in writing between genders for the Lab 11 experimental design ($p>0.5796$). Final paper grades were not significantly different by gender, nor were the paper draft grades. The student's year in school had no significant effect on any variable related to student writing that was tested. At this point it is not clear how to interpret these differences due to gender.

As we might expect from similar low-stakes writing assignments, there was a strong and significant correlation between the quality of Lab 10 and Lab 11 experimental designs ($r=0.40899$, $p>0.0035$). However, there was only a weak but significant correlation between the quality of Lab10 experimental design and students' final paper grades ($r=0.37274$, $p>0.0083$) and no correlation between Lab 11 experimental design and paper grades, nor between any in-class writing and draft grades. This may be due to inherent differences in the kind of writing that students are doing. In class writing such as the experimental design is less formal and its purpose is to help students better conduct an experiment. Unlike in class writing, in which there is little time for revision, formal papers written outside of class require more time and careful construction. At this point, students are reflecting on their experiments and attempting to place their results in a more global context. However, the correlation between the quality of the students' first experimental design and the final paper is significant, and this may be important in that it is during the first lab that students plan their experiment. If the experiment is well designed, this may contribute to a better final paper. There was no correlation between students' grades on their drafts and their final paper grades (r=0.18131, p>0.2125). The quality of students' writing did change substantially from draft to final paper, depending on the draft feedback and effort put into the final paper, so this result was not unexpected. Surprisingly, there were no strong or significant correlations between student group and the quality of in-class writing or between student group and final paper grades.

Supporting our hypothesis, there was a positive affect of having guided questions with designing an inquiry experiment, as shown by a significant difference in quality of students' in-class written experimental designs between the treatment and control groups (19.943 versus 17.943; p>0.0489). However, draft (22.337 versus 18.929; p>0.0760) and paper grades (27.186 versus 27.971; p>0.6726) did not vary significantly whether or not students were provided with the guided questions. There were several intervening and potentially confounding factors, due to the nature of the paper writing process in our labs, which included peer review of paper drafts that were not limited to students within the treatment and control groups.

Student attitude survey

Student survey results indicated that 82.9% of the students provided with the guided questions used the questions, and of these students, 80.4% of the students reported that the guided questions positively affected their experimental designs. The three most frequent responses to each survey question are summarized in Table 1.

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