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Laboratory Materials: Affordances or Constraints?

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Abstract: Laboratory instruction is critical to the understanding of biology and is a central piece of biological sciences instruction. Although much investigation has focused on the content of biology laboratory exercises, we contend that understanding the extent to which the laboratory materials can aid or limit experimental investigation is of equal importance. In this study, therefore, we investigate the role of timing and availability of laboratory equipment in the context of two different laboratory exercises. We use both case study and an experimental approach to investigate how laboratory materials guide the planning, context, creativity, and timing of ideas shared among students. Our data support the notion that providing students with laboratory equipment before students plan and consider different experimental approaches can constrain students' ideas and encourage tool-focused solutions to experimental design tasks. © 2011 Wiley Periodicals, Inc. J Res Sci Teach 48: 1010–1025, 2011
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Critical to the study of biology is an understanding of laboratory techniques that engage students in critical problem solving and scientific reasoning (National Research Council (NRC) 2003, 2005). In a landscape characterized by rapid interdisciplinary advancements and technological change, undergraduate academic institutions have been slow to provide students with adequate laboratory experiences (NRC, 1999, 2005). With increased appreciation for the scholarship of teaching, however, more faculty have been engaged in the study of undergraduate biological education (e.g., D'Avanzo, 2003; Handelsman et al., 2004; Jordan, Rousch, & Howe, 2006). Much of the research to date, however, has focused on the content of the learning experience in contrast to the procedures involved in setting the learning context. The goal of the two studies reported here was to explore the provisioning of learning affordances (i.e., laboratory materials) on scientific inquiry practices. First, we investigated reasoning about a scientific inquiry task among small groups of students and between students and experts. We accomplished this through analysis of their discourse. Finally, we studied differences in inquiry practices between groups of students who were either provided or not provided with these laboratory affordances.

Learning affordances are provided by elements, including physical objects, within the learning environment that provide opportunities for accomplishing particular kinds of actions. Sociocultural theorists have extended this notion to considering the role of affordances in learning (Cole & Engeström, 1993). Gibson (1977) first introduced these terms within cognitive psychology to describe opportunities for action based on perceptions of the environment. Others (e.g., Norman, 1999) have added to this notion such that these affordances can guide how learners engage in a task. This research is concerned

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with the ways that instructors direct the appropriation of supplies during a classroom-based biology laboratory experience. In typical laboratory experiences, students are provided with a series of instructions and suggestions for materials necessary to complete the laboratory task (e.g., Vodopich & Moore, 2001). We consider these instructions and materials as affordances and constraints that can directly affect the learning experience.

A major affordance provided during the laboratory experience is the laboratory manual, which tends to highlight scientific process skills. In particular, these manuals focus on activities that help learners to reason about experimental design, hypotheses, and data interpretation (e.g., Vodopich & Moore, 2001). Indeed, fostering these inquiry skills are considered major goals of laboratory instruction (Hofstein & Lunetta, 2004) but certain characteristics, such as the instructions provided in the laboratory manual, can provide constraints on laboratory completion by focusing student attention on the procedures without considering broader contexts or creative solutions (reviewed in Hofstein & Lunetta, 2004).

This constrained approach likely stems from three driving factors: the procedural focus of the laboratory task, a disconnect between instructor and student goals for the laboratory experience, and a focus on laboratory materials, including the laboratory manual and the associated equipment provided to complete the task. The first factor, termed the ‘‘cookbook’’ mentality, leads students to focus on task completion instead of thinking about the experimental outcomes and global goals (Schamel & Ayres, 1992). The second factor is that instructor and student expectations for laboratory goals appear to differ (e.g., Chang & Lederman, 1994). Although instructors tend to view the broader context of the inquiry experience, students tend to view task completion as the major goal. Finally, laboratory equipment is almost always provided along with the laboratory manual and can serve to distract students from bigger ideas. Hofstein and Lunetta (2004) noted that students, during the laboratory experience, tend to focus on ‘‘manipulating equipment but not manipulating ideas’’ (p. 39).

The goal of engaging students with inquiry practices such as experimental design, hypotheses testing, and data interpretation (Duschl, 2008) through laboratory experiences is not an easy one to achieve. Students have difficulty asking productive science-related questions (Marbach-Ad & Sokolove, 2000). In addition, students often have trouble articulating how evidence can be used to support scientific claims (Ryder, Leach, & Driver, 1999).

There is evidence, however, to suggest that movement away from cookbook procedures can enable deeper involvement in inquiry that better mirrors authentic scientific practice (Lord & Orkwiszewski, 2006). Little research, however, has addressed the appropriation of laboratory tools with respect to reasoning and timing. If students fail to take advantage affordances in productive ways, they might miss the opportunity to generate original research questions and subsequently design investigations to test these ideas.

Research Objective

Given this relationship between cookbook mentality, task completion, and learning affordances, we investigate here how laboratory materials influence student activities with respect to problem solving in the context of a typical teaching laboratory. Although we acknowledge that other aspects of the laboratory learning environment, especially the social milieu, can serve to afford or constrain student learning, we chose to limit our study to the means by which both expert and novice students discuss the task at hand with particular focus on materials. We chose this focus because, if our goal is to help students engage in more expert scientific practices, then it is reasonable to understand how experts and novices differ in how they approach a laboratory investigation (Chinn & Malhotra, 2002; Hmelo-Silver, Nagarajan, & Day, 2002; Nersessian, 1995). To accomplish this, we examined the nature of expert and novice student discourse as they engaged in an experimental design task. The experts were two advanced biological science graduate students who had a background in ethology and the experimental task required some interpretation of the behavior of the animals investigated. We compared this with undergraduate and novice graduate students' discussion as the engaged in the same task. These students had exposure to introductory biology but not to the detailed methods of ethology. Based on our findings, we completed a second investigation in which we studied student activity as we manipulated access to materials during novel laboratory task. We focused on the context of the student discussions, the nature of experimental planning, and the creativity of solutions used.

Creativity, Context, and Planning in the Laboratory

We situate this research both in calls for curricular reform and increasing emphasis on inquiry practices. Recent curricular reforms indicate a strong need for students to be engaged not only with science content but also with opportunities to reason about scientific phenomena (e.g., Krajcik, Czerniak, & Berger, 1998; Etkina et al., 2006; Polman, 2000). Learning experiences that foster students' refinement of ideas based on previous knowledge while enabling them to shape new ideas is again consistent with constructivist approaches to teaching and should enable students to move beyond static knowledge construction (Driver, 1995). Students should be able to generate and test ideas and construct explanations based on evidence (NRC, 1999). In this article, we discuss scientific reasoning as it pertains to experimental problem solving. Therefore, we consider reasoning tasks involved with planning, design, and interpretation (Lunetta & Tamir, 1979 for further description). In particular based on the notion of authentic inquiry (e.g., Chinn & Malhotra, 2002; Etkina et al., 2010), we focused on: planning, context in which experimental plans were discussed, and creativity in design solutions. We discuss these below.

Planning

Experimental planning stems from the identification of goals and the means by which to attain these. When testing ideas, it is common for both students and teachers to identify goals of their task, often, but not always, in the form of explanations or hypotheses (e.g., Jordan et al., 2006). In a study of six secondary schools in Australia, Wilkinson and Ward (1997) found that students often did not share a similar sense of task goals when compared to their teachers. Further, these researchers demonstrated differences in how students view goals depending on their level of achievement. High achievers tended to believe the more important aim of laboratory work centers on the opportunity to gain practice in the following categories, "accurate observations and interpreting them" and in "discover[ing] and verify[-ing] facts and ideas for themselves." In contrast, low achievers tended to rate the more important aim of laboratory work being to "make science more interesting and enjoyable through actual experience." These data indicate not only differing views of laboratory goals between students and teachers but also between students who experience different levels of achievement.

When, however, students are exposed to a constructivist learning laboratory, considerable discussion could be devoted to discussion of goals and task planning. Roth (1994) describes an inquiry-oriented learning environment where students devote time to "framing" research questions and in developing "narrative" accounts of observations. These questions and narratives provide evidence through theory building. The nature of the discourse during this planning was related by the author to the everyday practice of both scientists and non-scientists during problem solving (Roth, 1994). It is unclear, however, to what extent the laboratory materials aided in the planning process.

Context

Driver, Newton, & Osborn (2000) describe productive engagement with scientific problems as they relate to the natural world. This global context is critical to not only establishing the relevancy of information but also to determining whether one's model of a particular phenomenon is consistent with other sources of information. Given the array of possible unproductive behaviors in a laboratory environment, one can imagine a number of opportunities to focus solely on the laboratory materials on hand including but not limited to: (a) adopting a recipe approach, (b) solely focusing on a single but often not productive task, (c) randomly using various materials with no productive outcome, (d) copying activities of others, or (e) not participating (Johnstone & Wham, 1982).

Constructing meaning within a laboratory task requires more than observing outcomes instead involving the linking of observations to broader disciplinary knowledge (e.g., Eberbach & Crowley, 2009). As noted in Reigosa and Jiménez-Aleixandre's (2007) case study which analyzed discourse using Lemke's (1990) notion of contextualizing practices, students were able to iteratively make meaning out of the laboratory experience by relating ideas among concepts and with what they observed. This means that students moved beyond the observations of the phenomena alone. Certainly taking a dynamic view of scientific knowledge can result in a more integrated and global understanding (Songer & Linn, 2006). If a task is viewed solely in the context of the lab bench, task completion could involve little critical thought (Gunstone, 1991).

Equally important as relating ideas to broader context, is moving beyond the single task at hand to a more global perspective. As Gunstone (1991) notes, to reconstruct theory and think about concepts in different ways, the students need to spend time engaging ideas rather than focusing entirely on the laboratory materials. In Gunstone's example, the laboratory apparatus serves as a distracter rather than an affordance and the end result may be a limitation of creative thought regarding problem solving.

Creativity

Creativity is important in the effort to make new discoveries in science (Dunbar, 1997). Dunbar describes creative scientific reasoning as involving small increments of conceptual change. Although laboratory materials can afford engagement in inquiry practices, they can also constrain creativity. Because laboratory materials are so often presented at the initiation of the laboratory experience, discussion and modification of ideas at a small scale may not occur. Rather students might opt to use a puzzle-solving approach, which implies a right answer by piecing together the material at hand.

Constraining student thought may not only limit creativity, but might serve to dampen student motivation to engage in thoughtful completion of the laboratory task. A sample of 371 Israeli high school students revealed a preference for an open-ended structure to laboratory exercises (Hofstein & Cohen, 1996). These preferred laboratory exercises offer students the opportunity to make individual choices with respect to the directions taken in the investigation. Encouraging students to think about experimental design in an open-ended way will necessarily have consequences for student control but could also enable students to move beyond the "cookbook" to a consideration of what experimental outcomes might mean with respect to task purpose and the development of theory. In addition, the opportunity to develop original solutions to problems can not only result in productive engagement but also can motivate students to do so (Schamel & Ayres, 1992).

Given the value of planning, global contexts, and creativity highlighted above, the appropriation of laboratory materials should be made in such a manner to allow these ideas to be explored. Little research, however, has addressed these ideas with respect to material appropriation. As previously mentioned, in this article, we sought to first understand the means by which students discuss an unstructured experimental design task with particular focus on the laboratory materials. Then we manipulated the delivery of laboratory materials in an effort to determine the extent to which laboratory materials influence experimental design solutions. Similar to Greene and Caracelli (1997), we believe that employing mixed-methods, and therefore evoking different paradigms, can result in new insight. In this article, we take a sequential approach to explore new ideas (described in Creswell, Plano Clark, Gutmann, & Hanson, 2003) and use the data generated as a means of triangulation. The result, we believe, has led us to draw novel conclusions about the way in which materials can be used in the teaching laboratory.

Study 1: Comparative Case Study

In this study, we address the research question; in what ways does expert student reasoning about a scientific problem differ from novice students? We compare expert graduate students to two types of novice students.

Methods

Participants. The participants in this study were five undergraduates, two physics graduate students, and two life science graduate students from a large public university. All graduate students were recruited from the research laboratries of the lead authors. While providing the researchers with a ready group of participants, the use of students within particular laboratory groups constrain our ability to generalize the nature of the conversation. We were, however, able to characterize differences among the groups based on the themes we identified. In doing so, we could generate ideas that were tested in the larger group.

All undergraduate students were science majors; four of the five were female. All of the graduate students were male. All participants had no experience with the particular task that we assigned for the study.

We designated two groupings, novices, and experts, based on two criteria: experience and credential (i.e., advanced degree). The novice grouping was further divided into beginners and intermediates. We did so following a rationale like that detailed in Schraagen (1990) where data support the notion that scientific expertise can be divided into those with no experience, those with experience in problem solving outside the domain of interest, and those with experience in problem solving within the domain of interest. The beginners consisted of the undergraduates who were divided into one pair and one triad. We labeled these as beginners given their inexperience and their lack of any credential in the subject. None of these students had experiences in conducting scientific research. The intermediate novices were the physics graduate students who were within the first 2 years of their graduate study, and although possessing a degree in science, had little (i.e., akin to the undergraduate novice pair and triad) experience in biology. Finally, we designated an expert pair. These individuals were biology graduate students who were in their first 2 years of graduate study. While they were unfamiliar with the task, these individuals have earned undergraduate degrees in the biological sciences and had ample experience in the sciences.

Procedure. The nine participants were recruited through courses taught by the authors and asked to come to a widely used teaching laboratory during a time when classes were not in session. These students were informed that they would participate in a research study, given lunch and a small stipend. These students were aware that they were not being assessed for any course. Via a typewritten page, we asked the three pairs and the triad to complete the same task and we provided them with identical sets of materials (Supporting information Appendix 1). No further instruction was given. All discussions were videotaped and then transcribed verbatim for analysis. The researchers were not present during the discussion but were available if problems arose.

Data Analysis. Given the value of planning, global contexts, and creativity highlighted above, we coded the transcripts for these categories (Table 1). The coding criteria were developed both deductively and inductively. The research that we reviewed earlier demonstrates the importance of these factors in laboratory practices and we looked for evidence of these themes. However, we were also alert to how evidence of these thematic categories would appear in the discourse, and our coding criteria were revised inductively to be useful in understand the data at hand. We compared the nature of the novice discussion to that of the experts with particular regard to the themes that emerged. To increase reliability, two different researchers coded the transcripts and met to discuss their codes until 100% agreement was attained (following that described in Johnson, Penny, Gordon, Shumate, & Fisher, 2005). These researchers followed a similar protocol to interpret the results. Finally, the two other authors reviewed these interpretations to ensure further agreement. Below we highlight examples of each type of code and contrast the nature of the conversation between the two groups.

Results

Below we characterize the concepts identified within each of the categories. We highlight the expert sequence first and then discuss context, planning, and creativity within each of the novice pairs/triad. Supporting quotes are given.

With respect to experimental design, our three thematic categories were able to differentiate the experts and novices. The expert pair showed clear differences with respect to the three themes when compared to the three novice pairs/triad, with their conversation demonstrating greater awareness of a global context, more distal planning, and more openness in regard to creativity. We found no differences, however, among the beginner and intermediate novices with regard to the three themes.

Table 1
Coding variables

Variable	Definition	Description	Example (from Study 1)
TTC	Time to completion	Minutes until paper turned in	[Study 2 only]
Context	Refers to the extent to which the discussion focuses on elements of the laboratory environment versus the elements beyond. In the case of the ethology task elements beyond likely refer to the habitat of the animals	0 = No discussion of variables 1 = Discussion of 1 variable constrained to immediate conditions 2 = Discussion of >1 constrained variables 3 = Discussion of variables extends beyond immediate conditions	Local: "Let's see if they [the study organisms] die or not. Let's see if [the organism] likes water." Global: "what might be the environment [the organisms] naturally live in?"
Planning	Refers to the extent to which the discussion focuses on experimental design, hypotheses, and outcomes with respect to the task goals versus a sole focus on the task with reference to laboratory materials alone	0 = No planning involved 1 = Discussion of instructions only 2 = Discussion of instructions and an experimental plan but with immediate agreement to suggestions 3 = Discussion and negotiation of experimental plan; often including experimental outcomes.	Proximate: "Let's look at what we have. . ." & "Why would we paint brush it in?. . .oh the paper's there just to. . ." Distal: "How will we measure preference?. Preference is a proxy for keeping them alive. . .I think we should have multiple trials. . ."
Creativity	The extent to which the discussion explores a number of experimental designs. In the context of the ethology experiment, the double-linked petri dish (while not the only piece of equipment available) appeared to constrain design to dichotomies	0–3 scale 0 = No solutions provided 1 = one solution provided 2 = two solutions provided but both use the same equipment and plan 3 = two distinct solutions based on different sets of equipment	Constrained: "[We] should set up two different solutions in here and then see where the bugs go to. . .why don't we put the two different textures in there and we can put them side by side and see which ones they go to" Open: "another way to score this, that we have decided not to do is. . ."

Context: Ideas Local to the Lab Bench or Beyond?

Our analysis indicated a contrast in the context in which the discussion focused. Whereas the experts typically discussed the environment in which the organisms lived, the novice pairs/triad most often discussed the interactions of the organisms *in situ*. In focusing on the local context, the students appeared limited in framing their ideas with respect to the general problem.

For example, the expert pair began by discussing a context beyond that of the equipment in front of them. They started by mentioning the main or global goal of the task, one of the team states, "Okay so we have to figure out what environment the isopods enjoy, thrive in.'' The team then restated these goals twice and they questioned what environmental characteristics in which they expect the isopods to thrive.

Later these experts discuss ideas in a broader context, by checking their expectation of isopod behavior based on their living environment:

> E1...depending on their native environment salt would either be important in maintaining their osmotic balance or detrimental... beneficial, or detrimental...
> E2: Based on the fact that these were collected from a moist terrestrial environment...
> E1: perhaps from under a rock or from somebody's lawn...
> E2: importantly none marine... I would guess that the excessive salt concentration over here would lead to excessive water loss...

These individuals are focusing on the natural environment of the organisms and can then use their expectations to guide their experimental manipulations.

In contrast to the expert pair, the novice pairs/triad discussions tended to focus entirely on the equipment in front of them. In all three, the discussion began with how they might use the materials and they later move into the task at hand. During this time, the novices tended to focus entirely on the interactions in front of them and only mentioned the environment of the animals after they were finished with their manipulations.

For example, the following discussion focuses on a trial and error type of actions:

> N1: they don't seem to be bothered...he doesn't like it... you can tell he doesn't like it...they didn't like it...
> N2: yea, he doesn't like the water at all...
> N1: here we go look at this guy, he likes the salt
> N2: they just travel back and forth
> N1: maybe he just likes it better over there
> [after some manipulation]
> N1: I don't know if they have a preference for the salt and the sugar or the light and the dark...
> N2: they really seem to be on both

The above conversation indicates an experimental focus entirely on the laboratory environment. These students generated a final report in which the materials provided are discussed, but there is no mention of the natural habitat. This pattern of discussion is mirrored by the other two sets of novices. In only two instances do the novices mention a context beyond the lab bench and in both instances, the pairs drew on ideas about how ''bugs'' like sugar based on personal experience. The context in which the students view the problems will likely have consequences for how these individuals plan to complete the task.

Planning: Using Materials or Supporting Ideas?

The groups differed to the extent they discussed the task with respect to testing ideas versus using the materials alone. The expert pair focused a large portion of their discussion on finding ways to test their ideas through experimental manipulations. After identifying the task, they discussed assumptions and predicted outcomes prior to conducting the experiments. The novices, in contrast, sought immediately to identify which task the materials might represent and subsequently created designs based on these ideas. The manipulations therefore were more like trial-and-error versus hypothesis testing. This was also noted in the intermediate novice pair.

The expert pair began by defining their question, and then determined what type of data will be collected. Furthermore, the expert pair recognized that the materials constrained their actual design. For example, one student stated, ''I think what we should do is have multiple trials of placing the isopods in the middle of this conveniently, I think our experimental design will be influenced by the materials we have... placing one or multiple isopods in the center, and having them, and measure how many." All of this discussion occurred prior to actual experimentation.

The novice pairs/triad, however, tended to discuss the task in a very different manner than the experts. Again, these novices began their investigation by focusing on the equipment made available:

> N1: How many different environments do we have?
> N2: What can we use this stuff for?
> N1: We have paintbrushes... so that's probably to put the solution on the surface.

From here, these students created manipulations that focused entirely on using all of the available materials. This is also evident by one of the other pair's conversation.

> N1: why do we need the timer?
> N2: I think we time it, I think we see how it long it takes if something dies quickly
> [After some playing around]
> N1: so this is the type of environment, we have foil. Plastic, foil, we have this screen
> N2: yeah are you trying to say that we should see which one they move on.

Following these materials-based discussions, the students then proceeded to their manipulations. In using the approach of following plans based on the materials provided, there are likely consequences for how creative the experimental solutions will be.

Creativity: Limited to the Materials or New Ideas?

Finally, our analysis indicated differences in the number of experiments designed. The expert pair was able to generate multiple designs for supporting their ideas. The novice pairs/triad, however, followed the materials only.

The expert students clearly discussed multiple ways in which data can be collected and further they discussed whether their observations make sense when checked against their knowledge of zoology:

> E1: Okay, so I mean what, you don't know anything about these animals, and even before you came into this experiment, you would assume that they liked the glucose right, based on your biological...
> E2: It's a basic energy source that many organisms use...
> E1: Okay, so that's a reasonable hypothesis to come up with...
> [After several minutes of toying with the materials]
> E1: We should be marking these every minute or so...
> E2: Another way to score this, that we have decided not to do is mark their location at each minute interval, that might be more precise to understand their decision making process, for example, they might over the course of a time period, move back and forth before settling... that sort of recording rubric would show that more

In this discussion, the expert pair is clearly using the materials to support ideas, but we argue they are using the materials to support rather than constrain design solutions. These students used the materials provided to come up with four very different ways of designing an experiment:

> E1: we can't be for certain that the acidic nature it is interacting with, it is enjoying... it could be for example, what kind of vinegar is it?
> E2: No, there are different kinds of vinegar, it's not balsamic vinegar
> E1: it can be any kind of vinegar, any compound of vinegar that it's going to
> E2: in order to generalize for the fact that it's enjoying the acid, you'd have to...

These experts then propose further design to tease apart whether it is the vinegar or acidic nature of the solution that might be an attractant to the organisms. Clearly, this addition to their design is not at all constrained by the materials.

The novices, however, kept all manipulations limited to their materials. All experiments in all three pairs/triad were conducted are in the form of a dichotomy, with only the nature of solution differing:

> N1: [We] should set up two different solutions in here and then see where the bugs go to
> N2: Why don't we put the two different textures in there and we can put them side by side and see which ones they go to.

Note that the students are limited to testing all ideas in "twos." Furthermore, almost all of the experiments were conducted in one versus another mode:

> N1: okay let's see if the sugar guy finds the acid
> N2: Or let's see if the other guy comes to the sugar. . .
> N1: I'm going to put, we can put the salt
> N2: Only thing they want to run on is this
> N1: And salt, and water
> N2: let me try the acid on these guys.

Beyond these dichotomies, none of the three pairs/triad discussed the implications of their conclusions. Discussions of the implications of their actions may enable the students to more productively direct future actions.

To conclude, the tools made available to the expert students did not dictate the way they proceeded, even though they were aware of the constraints imposed by the context. These experts also appeared to be more driven by their questions than by task completion. In contrast, the tools made available to the novice students appeared to strongly guide their experimental design. Each of the three pairs/triad kept much of their discussions to the context of the laboratory materials and followed entirely dichotomous designs and they proceeded through what appeared to be trial and error versus discussion of theory and hypothesis testing. This trial and error approach was also noticed in the intermediate novice group who had previous experience in experimental design. When reviewing the experimental design solutions of this expert pair one of us with ethological training (RCJ) was able to confirm that the expert design would likely result in a productive means by which the organisms could be held in captivity whereas none of the design solutions of the novice pair would likely prove productive.

There were clear distinctions between experts and novices based on these variables; which led us to suggest that the equipment may be limiting student discussion. Furthermore, we considered to what extent prior planning and discussion might relate to the design of experiments in terms of time spent completing tasks. Given that many life science laboratories are held within time constraints, we hypothesized that allowing students to plan in the absence of laboratory materials might result in faster time spent on solving the experimental task when compared to the group that was given the laboratory materials. We based this on the notion that students would spend less time playing with the tools and more time devoted directly to the task.

Study 2: An Experimental Test of the Role of Materials in the Laboratory

In this study, we address the research question; will the removal of laboratory materials during initial discussions result in more planning, creativity, and ideas that are not tied to the lab bench? More specifically, we test the hypothesis that encouraging discussion prior to dissemination of the laboratory materials would result in more sophisticated (i.e., compared to expert) discussions with respect to planning, creativity, and context. In addition, because timing is often of concern in classroom laboratory settings, we chose to compare time to completion between the two groups. We hypothesized that by directing the students to more sophisticated activities time to task completion will decrease.

Methods

Participants. For this task, we recruited 48 students from three science teaching methods courses who volunteered to participate in this study. No incentives were necessary. These students were, in general, junior, and senior undergraduates who have identified themselves as pre-service science teachers. The number of male to female students was roughly even and mixed among the groups. All volunteers were randomly divided into 24 pairs.

Procedure. When students entered the laboratory, they were first divided into two groups. The first group was randomly assigned a task with materials listed and the other group was assigned a task without materials listed. For this task, students were asked to design two experiments to determine transpiration rate using stem cuttings from a single species of plant. In addition, they were asked to articulate further what they might need to know to be more successful in determining the transpiration rate. One group, termed "with materials," was given the following pieces of equipment to use in planning their experiment: water, beaker holding plant cuttings, Parafilm®, tubing, ring stand, graduated pipette, timers, humidity sensor, cup, cup with hole, scissors, and two droppers. They were, however, instructed not to begin any experiments. The other group, termed "without materials" was not given any materials. Both groups were given the exact same task: record time to completion, describe each experiment, provide drawings of the experimental set up, and comment on their thoughts as they completed the task. Aside from the task, the students were prompted to "think aloud" during their discussion so that the other individual could hear their ideas which enabled the pair to generate a statement about how they completed the task. We then asked students to turn in a written report for analysis as a pair.

Given the large sample of students participating in the study, it was not feasible to video record and transcribe student practices. We, however, acknowledge that by asking students to turn in a written report, we are adding an additional source of variability to our student when compared to direct video analysis. One pair member needed to accurately reflect the nature of the conversation and solution which relies on that students' comprehension of the task and their ability to communicate ideas in a timely manner. Such variability might limit the ability to statistically detect differences between the control and treatment groups. Because we were able to detect such a difference (see below), this additional step did not greatly affect our ability to draw conclusions.

Data Analysis. We were particularly interested in three variables: planning, context, and creativity identified in Study 1. We remained particularly interested in these variables because of the value of global and creative planning to experimental design, hypothesis generation, and data interpretation. In addition, we measured time to completion. Although not a direct focus of our study, we suspected that the students without the materials might engage in deeper discussions and therefore take more time.

We coded the written data according to Table 1. The definitions are the same as in the first study; however, the means of coding differed slightly given that the subject products were written reports rather than transcripts. We assigned a single value for each coding category to each report. All the data were coded by two coders. All discrepancies were resolved through discussion until agreement reached 100%. TTC represents time to completion and is given in minutes. TTC was compared using analysis of variance (ANOVA) with experimental condition (with or without materials) as the between subjects factor. We also compared the groups on each of the three other variables using a 2×3 ANOVA with experimental group as a between subject factor and coding category as a within subject factor. We chose to conduct two ANOVAs because of the different scales/variances of the timing versus coded variables. For both comparisons, $\alpha = 0.05$.

Results

Average scores and SD (in parentheses) across 12 groups in each treatment (i.e., with or without materials) are presented in Table 2. Students with materials took significantly longer [$F(1, 23) = 34.49$, $p < 0.001$] than those without the materials. In addition, significant differences occurred within the two groups when considering planning, context, and creativity [$F(1, 71) = 22.23$, $p < 0.001$].

With respect to planning, when asked to comment on their report, the group without materials reported more discussion beyond the actual instructions and that they discussed the problems and plans immediately after reading the task statement. With respect to context, the students without the materials more often mentioned the natural environment (i.e., global context) of the plants (i.e., 10 compared to

Table 2
Controlled experiment average

	With Materials	Without Materials
TTC	27.17 (4.82)	14.33 (5.84)
Planning	1.50 (0.52)	2.25 (0.62)
Context	2.00 (0.74)	2.75 (0.62)
Creativity	1.83 (0.83)	2.58 (0.67)

four instances). This level of global discussion was written in the section where students considered what more they needed to know and what directions they would consider. The students with the materials tended to write about local conditions.

Finally, we examined indicators of creativity. We found differences in the number and the soundness of the solutions posed (i.e., creativity). All students in the group with materials provided a very standard solution of measuring water lost to the plant (i.e., measure water taken up by the plant). But only three of these groups were able to provide a second solution that was truly different from the first (involving water being lost through the leaves). In total, we found only two types of solutions were posed by all 12 groups. This is in contrast to the groups without materials which in total provided seven novel solutions (i.e., two involving measuring water uptake, three involving water lost through the leaves, one involving pressure, and one involving weight). In the absence of materials, eight groups generated two different solutions from each other and one group generated no viable solution. In total, the 24 students without materials generated similar solutions to those provided by the materials group as well as five additional measures.

Discussion

In summary, our case analysis indicated that novice groups, when posed with a typical laboratory-based experimental task are likely to quickly focus on the available materials, procedures, and narrower contexts when compared to the directed and global discussion of the expert group. Further, our controlled experiment supports the notion that removal of the laboratory material can result in greater planning and more context general and creative solutions. This effect was evident even though students were naïve to the given tasks. Below we discuss each variable of interest separately and then more generally we discuss ideas about experts and novices.

Planning

Consistent with the situative perspective on learning (Greeno, 1998), we suggest that when creating a laboratory exercise, affordances, and constraints should be considered. This is important in the task statement as is the available equipment. Would the novices in our study have behaved differently had we not stated "Using the available materials..." in our task statement? The students appeared to immediately focus on the materials. While the usual intention of laboratory materials is to afford the design of the experience and enable broader interpretation and evaluation, the way in which we present materials might constrain student thinking; especially given that students may not be motivated to seek broader meaning.

We also argue that a focus on task completion is inconsistent with a constructivist perspective in which deep learning is active and builds on previous experience (Palincsar, 1998). Resulting knowledge structures from a sole focus on task completion are, therefore, likely to be shallow. Task completion is not likely to motivate further learning. Simply reproducing knowledge fails to encourage adaptive motivations which promote the desire to engage in deeper learning challenges (Pintrich, Marx, & Boyle, 1993). Clearly learning affordances can affect goal orientation which critical to learning (e.g., Pintrich & Schunk, 2002; Ames, 1992).

Context

The results of our study suggest the potential for the laboratory experience to move beyond the procedures used by scientists and provide the opportunity to investigate ideas and solve problems

(Hodson, 1993). To create these opportunities, however, the learning environment must be designed through careful consideration of learning theory [e.g., Bereiter (1990)]. For example, providing students with time to reflect (Miller & Driver, 1987), and solving authentic problems (Brown, Collins, & Duguid, 1989), may encourage them to attend to broader goals and contexts. Such an open-ended approach may also be consistent with student preference (Hofstein & Cohen, 1996). In many cases, however, recommendations focus on the intrapersonal aspects of the learning environment (e.g., Donovan & Hemingway, 2008) versus the physical aspects of the learning tasks. Our data suggest that the simple act of having laboratory material available to students can greatly influence the outcome of the learning experience.

Creativity

Although scientists rarely operate in the absence of materials to direct ideas, it is clear that scientific experts are able to solve problems using, but not being limited by, these materials. In context of a student laboratory, perhaps withholding materials and encouraging discussion would focus attention towards broader goals and outcomes of experimentation, which is critical to making wise use of time spent in the laboratory (see review in Hofstein & Lunetta, 2004). Certainly, one would not be able to provide the necessary material to test all of the ideas posed by the students, but we argue that the act of planning and framing the problem can promote greater abstraction (i.e., more global thinking). In doing so, maybe the student will be better able to view the materials as affordances rather than constraints.

Experts and Novices

It is not surprising, based on other studies that experts in our study would use a different experimental approach when compared to the novices (e.g., Dunbar, 1993; Hmelo-Silver et al., 2002). Similar to our study, Hmelo-Silver et al. (2002) found experts addressed the problem statement more clearly, and focused on more global aspects of the problem (i.e., beyond the laboratory environment). What is relevant to our work, however, is the fact that these researchers also found similar levels of metacognitive discourse and that experts were only slightly more likely to refer to prior knowledge. Furthermore, in their study, the experts and novices were able to reach similar solutions. The experts, however, were more likely to discuss data interpretation. These data suggest that framing of the problem statement and goals, and discussion at several levels of abstraction are at least as critical as prior knowledge, if deeper interpretation and evaluation of the data generated by laboratory experiments is a major goal (see also Roth, 1994 for discussion).

What is notable about our data was that the intermediate group did not appear to frame the problem statement in any way different from the beginners causing us to either believe: that the nature of this task lends itself to little difference among novices or that the intermediate group perhaps did not have the level of expertise in the type of experimentation required in the task. Given the nature of the discourse, we suspect the latter but we did not test for prior knowledge or experience. In contrast to the variability in study 1, we found in the controlled experiment that with likely similar levels of prior knowledge, the group that was given no other option but to discuss the problem statement and experimental plans were more likely to provide less context-specific ideas. The lack of emphasis on the tools at the lab bench may have served as an encouragement for the students to frame ideas akin to the approach used by experts, even though these students may not share the same motivations.

Given that our experts allocated time to discussion and planning multiple designs, we expected that the group without materials would take longer to complete the task in the controlled experiment because their discussion would more closely approximate that of the experts. On the contrary, we found that the students with the materials took longer to the complete the task. When looking at the field notes taken by the lead author during the experiment, it was obvious that the group with the materials allocated a much of their time to discussing and ‘‘playing’’ with the materials. This aspect of the conversation did not appear productive in that the discourse did not lend itself to the experimental design. In this manner, the materials appeared to solely distract the students from the task. More data are necessary to support this notion.

Conclusions

Reviews of laboratory instruction at both secondary and post-secondary levels indicated several challenges and opportunities to provide students with the chance to plan, relate ideas to a global context, and pose original solutions (NRC, 2003, 2005). At the forefront of these challenges, perhaps, is providing students with explicit expectations about what students should be learning during the laboratory experience. So often the purpose of the laboratory experience can be unclear to the students and the teacher (NRC, 2005). We contend that science laboratories should offer students the opportunity to explore scientific epistemology (van den Berg, Katu, & Lunetta, 1994), and therefore scaffold the ways in which scientists: discuss the experimental context, explore experimental design, and plan experimental tests.

In providing students with the opportunity to plan, broadly relate ideas, and pose solutions, certain issues may be encountered. First, laboratory exercises in the face of varied classroom activities and objectives (see review in Linn, 2003) may not always lend themselves to links with other classroom activity. Providing students with the time to establish and modify their plans can, therefore, be difficult. A certain level of flexibility must be explored. Second, encouraging students to explore the global context in which scientific claims are generated often takes the form of engagement with real-world science. Yet, authentic scientific practices can result in vague, complex, and sometimes confusing experiences that are not typical of the classroom experience (Millar, 2004) and can appear to contradict known classroom ideas (Hammer, 1997), for example, when students generate a laboratory result that does not match what was read in a textbook. Teachers must find the means to allow students to deal with anomalous data which can be difficult (e.g., Chinn & Brewer, 1993) but we argue is likely necessary if we expect students to generalize and transfer ideas to novel contexts (e.g., Holyoak & Thagard, 1997). If we are to deal with these uncomfortable complexities and contradictions, however, reflection is likely necessary but can be overlooked by teachers (e.g., DeCarlo & Rubba, 1994). Finally, allowing students the freedom to explore novel solutions can be difficult, especially when a focus on procedures might be necessary because of the nature of the experimentation which may require very detailed procedures (Tobin & Gallagher, 1987) or because of safety (Hayes, Smith, & Eick, 2005). Yet, if we accept the view that making novel connections can encourage thinking akin to the means by which scientists gain insight (Dunbar, 1997), then opportunities to independently explore ideas without constraint must be provided. Clearly, a balance where students are taught specific procedures should be maintained with students exploring their own ideas.

We argue that engaging students in the epistemic practices of scientists is one of the most important goals of the laboratory experience. These practices (i.e., planning, thinking beyond the lab bench, and exercising creativity) can result in the development of ideas that can lead to discovery and conceptual change (Dunbar, 1997). While we acknowledge that there are constraints, such as those listed above, other studies support the notion that laboratory experiences have the potential to provide students with rich and practical science reasoning experience while working within confines (e.g., Hofstein & Lunetta, 1982; NRC, 2005). Certainly providing students with less structure has been shown to result in greater planning, more creative designing and hypothesis forming, and more globally oriented interpreting skill (e.g., Roth & Roychoudhury, 1993). Doing so may also help to structure laboratory experiences in ways to avoid students taking an entirely "cookbook" strategy to their work (Roth, 1994).

Based on our results, we argue that students need opportunities to engage in thinking that moves beyond procedure. Perhaps allowing students to engage with laboratory materials in a manner more like out-of-school expert practice (i.e., allowing time to generate ideas, plan, and exercise creativity) would encourage more thoughtful appropriation of ideas. Our results, in combination with previous research warrant future investigation into the relationship between laboratory materials and the development of scientific practice skills. More specifically, hypotheses about the sequence in which affordances are presented, or perhaps even chosen by the student, can be tested. The consequences of how we decided when to encourage students to take time to plan and reflect could also be measured. Might future investigations explore how these links can be better made in a classroom context? Lastly, while we have supported the notion that the affordances typically given to students in a laboratory experience could serve to constrain ideas, we need to better understand how greater planning, context, and creativity relates to other aspects of inquiry practices.

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