# Considerations for Effective Laboratory Instruction in Science Classrooms, As Inspired by Metacognition

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**Abstract:** There are many designs for laboratories that can be effective. Teachers should be able to design labs that are both grounded in methods identified by research as effective, and are efficient for their learning goals and context. Evidence of students' metacognition should be used to evaluate different lab components and styles. Some merits and limitations of full scale inquiry laboratory styles, simplified inquiry laboratory styles focused on scaffolding specific skills, and some major additions to simple labs are identified. Furthermore, essential components of good laboratory design which are necessary for "meaningful learning" are proposed. The reader will be able to identify what should be considered when choosing a lab style, and components that should be included for meaningful learning.

## Introduction

The question of how to design effective laboratory experiences for students has been a topic of interest for decades (Coker, 2017; Dushl, 1994). Modern science standards require that students learn practices associated with scientific inquiry, and require teachers to inspire interest in science (Holmes, Hunter, & Schklar, 2011). However, the definition of inquiry is complex: it includes asking questions, planning and conducting investigations, finding solutions to problems, and analyzing evidence to help make predictions or give scientific explanations for outcomes. How can instructors best foster such a complex practice? The research suggests a few general lab instruction structures that can effectively scaffold students' learning of these practices, each having their own merits (Abdisa & Getinet, 2012; Bakker & Akkerman, 2013; Kung & Linder, 2007; Wong, Kwan, Hodson, & Yung, 2008).

One common method of supporting students' acquisition of scientific inquiry skills is through the promotion of metacognition (Kaberman & Dori, 2009; Kipnis & Hofstein, 2008; Kuhn & Dean, 2004). Metacognition has been defined as reflecting on your own thinking and reasoning. Students developing effective metacognitive skills are able to identify what knowledge they and their peers possess, to identify common strategies for applying, acquiring and communicating that knowledge, to plan the best practices, and to check for errors. Kung and Linder (2007) argue that the process of acting on metacognition to support reflection is the tool's essential function, so the final step in applying metacognition is taking action based on these abilities; the lab provides an environment in which students might do so.

**Several** different methods of evaluating lab effectiveness have been presented. Some papers suggest that educators focus on teaching the nature of science (Wong et al., 2008). Others suggest that labs are an effective way to teach scientific knowledge (Abdisa & Getinet, 2012), and a few propose using labs to support students' ability to transfer concepts to other scenarios (Bakker & Akkerman, 2013). The goals for developing good metacognitive skills align with the goals of both the modern teaching standards requirement to teach strong critical thinking skills, and the goals for labs presented above (Kaberman & Dori, 2009; Kipnis & Hofstein, 2008; Kung & Linder, 2007). Because of the alignment between the goals for labs and metacognitive skills, evidence of students appropriately applying metacognition will be used as a tool for evaluating a lab design's effectiveness in this paper.

Designing laboratory assignments for students can seem a daunting task. This is particularly true at the beginning of a teaching career as the standards often leave the task of determining the best teaching method to the teacher. This article will discuss the merits and limitations of a few general lab designs to help determine what the best style for different situations.

## Essential Components

Although research disagrees on what the best lab instruction might be, there is agreement on certain components that need to be included. For example, regardless of which style of lab a teacher decides to use, it is important that they are clear about which learning goals they are trying to teach, and that they communicate those goals clearly to students (Davidowitz & Rollnick, 2003; Ottander & Grelsson, 2006). If the goals of the lab are not made clear, students will often focus on the wrong learning objectives while trying to perform the lab, and may even choose to focus on skills that were not in the original design (Ottander & Grelsson, 2006). Supporting this point, Davidowitz and Rollnick (2003) also found that students' interpretations of the purpose of the lab can influence how they perform it. For similar reasons, Dori and Kaberman (2009) also suggest that more directly modeling both scientific reasoning and metacognitive reasoning results in a greater probability of students developing effective reasoning of their own. As such, clear communication of the labs goals and preparation with metacognitive skills are an essential component of good lab design.

Another important components that should always be included is guided reflection. This includes questions designed to guide students' reflection on both their explanations of how a phenomenon works, and on what skills they used to find this information (Bakker & Akkerman, 2013; Coker, 2017; Kipnis & Hofstein, 2008; Kung & Linder, 2007; Wong et al., 2008). Reflection should be designed to allow students to use metacognition to evaluate their own perspectives and understanding, as well as to evaluate the results for completeness or errors through considering different perspectives (Kipnis & Hofstein, 2008; Kung & Linder, 2007). Additionally, reflection should be used to scaffold students' consideration of different methods of extending their understanding to new scenarios (Bakker & Akkerman, 2013; Kipnis & Hofstein, 2008; Wong et al., 2008). These extra connections help make the laboratory a more meaningful learning experience. In fact, the authors who support inquiry-based lab structures often also refer to reflection as the most important part of the laboratory experience (Kipnis & Hofstein, 2008; Kung & Linder, 2007; Pyatt & Sims, 2012).

Other research suggests that in order for students to appropriately practice scientific inquiry skills, they must learn and internalize certain components of the nature of science (Coker, 2017; Kipnis & Hofstein, 2008; Wong et al., 2008). Many components of the nature of science treat metacognition skills as essential to the general process of developing scientific knowledge. These include an understanding that scientific knowledge is tentative in nature, that there are several processes for practicing science which can be effective in different scenarios, and that scientific laws and theories must be supported by evidence and checked for consistency with observation (National Science Teachers Association, 2000; Wong et al., 2008). This research suggests that designing a lab to support some or all of these understandings of the nature of science will help students to understand the importance of metacognitive skills and will inspire students to practice those skills during reflection.

Finally, every lab should give students opportunities to collaborate with their classmates (Davidowitz & Rollnick, 2003; Kipnis & Hofstein, 2008; Kung & Linder, 2007). Students who are collaborating have access to additional perspectives and reasoning to help them construct deeper understandings of the concept (Davidowitz & Rollnick, 2003; Kung & Linder, 2007). This is necessary to support higher quality reflection. Additional perspectives also allow students to practice the metacognitive skill of comparing their explanation with those of their peers, to identify gaps in understanding (Kipnis & Hofstein, 2008; Kung & Linder, 2007). Moreover, to properly collaborate, students must rearrange their own understanding into structures that can be effectively communicated, another key metacognitive skill (Kung & Linder, 2007). In this way, the key components of any lab design – clear goals, guided reflection, a focus on the nature of science, a focus on collaboration, and a metacognitive focus -- build off each other to create a more effective whole.

## Proposed Lab Structures

### *Full-Scale Inquiry Labs*

Within full-scale inquiry labs, students enact the entire scientific method. They ask their own questions, create their own hypotheses, plan labs to test the hypothesis, collect data, and analyze the data to reach meaningful conclusions. Research has suggested that for high-quality learning, it is necessary for students to enact authentic lab structures, as students' successful scientific reasoning is correlated to "how science is taught, not how much content is taught" (Coker, 2017, p. 15). Full-scale inquiry designs explore one entire method of acquiring scientific knowledge and therefore are the most authentic design proposed.

There are multiple merits of this design including that it is the most effective for helping students to develop better planning skills, it supports better transfer to new scenarios, it can help improve students' self-efficacy, and it can be used to scaffold the entire range of skills required by the Ohio state standards (Coker, 2017; Holmes et al., 2011; Kipnis & Hofstein, 2008). To incorporate reflection and metacognition, such labs should be designed to allow students to reflect on their actions and to form understandings after each section of the scientific method is used (Coker, 2017; Kipnis & Hofstein, 2008). Furthermore, many of the actions that make up the components of the full-inquiry lab give students practice with skills that are part of the overlap between metacognition and the modern teaching standards. These skills include asking questions, correcting errors, justifying opinions and current methods, and planning new or alternative procedures (Kipnis & Hofstein, 2008). Research comparing several lab designs suggests that this style of lab has the greatest potential for meaningful learning (Abdisa & Getinet, 2012; Kung & Linder, 2007). In particular, Kung and Linder found that this lab design might result in the most common use of metacognitive practices that result in meaningful reflection.

Unfortunately, this style of lab also can be one of the most challenging to implement in the classroom. This lab design can be very effective, but can also be difficult to use. The first major concern teachers express is that having students perform all of the necessary steps of scientific inquiry is very time consuming. Coker (2017) suggests that only approximately four labs per semester could be done if this method is used properly. Furthermore, Coker found that the greatest improvements in scientific reasoning skills occur in the first two uses of the full-scale lab design, and thus that it should be used at least twice per year. Kipnis and Hofstein (2008) warn that the factors that impact the success of a full-scale inquiry lab are complex, and are strongly dependent on the students' motivation to use laboratory time effectively. The availability of materials may also restrict the options that students have in choosing what experiments can be conducted (Coker, 2017; Wong et al., 2008). Furthermore, properly communicating the purpose and scaffolding the improvement of skills in scientific reasoning can be difficult if students are unfamiliar with this style of lab (Kung & Linder, 2007; Ottander & Grelsson, 2006). Because of these challenges to implementation, although a full-scale lab is the most authentic, it is not the only design that should be considered.

## *Focused-Inquiry Labs*

When using focused inquiry labs the scientific method may be slightly simplified or guided to focus instruction on one or more component or skill associated with the nature of science. Research suggests that these focused inquiry labs can still be effective at teaching the nature of science, provided that all components are addressed (Davidowitz & Rollnick, 2003; Pyatt & Sims, 2012). Further, some research suggests that focusing on specific components can reduce cognitive load (Pyatt & Sims, 2012), allow for more focused instruction on skills that need improvement (Kaberman & Dori, 2009), and include specific tools to support skill development (Davidowitz & Rollnick, 2003). The research generally offers examples of focused inquiry labs that effectively teach one component of metacognition at a time. For example, Kaberman and Dori (2009) found that focused instruction can be used to effectively scaffold generating questions that help students reach a deeper understanding, strengthened student's ability to construct models of compounds, and deepened students' understanding of scientific concepts. In another example, Davidowitz and Rollnick (2003) found that guiding students to diagram their own plan for completing the lab can significantly improve their ability to check for errors in their process and results. Once again, this is important as these metacognitive skill overlap with the inquiry process (Kipnis & Hofstein, 2008).

Focused-inquiry labs offer a great deal of flexibility in form, and in the style that the lab can take. However, research suggests that there are some limits to this approach, which cluster around the students' understanding and internalization of the skills on which the labs are focused (Davidowitz & Rollnick, 2003; Kaberman & Dori, 2009; Ottander & Grelsson, 2006). Because focused-inquiry labs focus on individual skill development, if students don't understand the purpose of a particular skill or believe that it is useful, this can negatively impact student learning (Davidowitz & Rollnick, 2003; Ottander & Grelsson, 2006). Moreover, research indicates that reflection and metacognitive activities that are externally imposed are often less effective than those generated by the students themselves (Kaberman & Dori, 2009; Kung & Linder, 2007). Research also suggests that skills must be presented through several different methods and tools to assist a wide range of students, which is not always achievable through these types of labs. A few effective strategies which can supplement focused-inquiry labs for this purpose include: the direct modeling of skills, the use of metaphors and case studies to explain processes and reasoning, the use of tables and flow charts to support planning and time usage, the use of physical modeling tools, and the use of group discussions (Davidowitz & Rollnick, 2003; Kaberman & Dori, 2009).

## Additions to Typical Labs

Oversimplified laboratory experiences where students simply follow directions and answer questions are the least effective option for teaching both metacognitive skills (Kung & Linder, 2007), and supporting content knowledge (Abdisa & Getinet, 2012). Unfortunately, there is strong indication that this lab style is prevalent in science classes throughout the country (Coker, 2017). Furthermore, research on the effectiveness of simply adding components to oversimplified labs to support metacognition and reflection has shown mixed results (Kung & Linder, 2007; McInerny, Boudreaux, Kryjevskaia, & Julin, 2014). These results are often either conflicting, or offer data that fall within the study's margin of error (meaning it is ambiguous), which has resulted in calls for additional research (McInerny et al., 2014). Nevertheless, some research suggests that a broad range of additions to labs might better support transfer of skills to new scenarios and offer additional perspectives to help students identify gaps in understanding in these varying settings (Bakker & Akkerman, 2013; Wong et al., 2008). A few proposals include: having students reflect on their results with internship supervisors as part of a lab (Bakker & Akkerman, 2013), or preparing for a lab through conducting a review of related historical scientific events (Wong et al., 2008).

One addition to labs that has been shown to be effective is the use of simulations (Kaberman & Dori, 2009; Pyatt & Sims, 2012). Pyatt and Sims (2012) propose that simulations are equally as effective as physical labs for supporting students' conceptual change. Their research claims simulations can provide both authentic scientific experiences and remove some extraneous factors to allow students to focus more efficiently on practicing metacognitive skills. In specific, it has been suggested that the simulation environment can be effective for supporting the question-generation and error-analysis components of metacognition (Kaberman & Dori, 2009). However, simulations should not stand on their own; good labs should still follow the inquiry process when possible, and simulations should be used to supplement or ease the implementation of this structure (Kaberman & Dori, 2009; Pyatt & Sims, 2012).

## Conclusion

The style of laboratory design should be grounded in what research states is effective, but should also be chosen to be the most effective option for your learning objectives and classroom setting. Although it might be the most effective design, not every lab needs to be a full-scale pursuit of the scientific method. Labs designed to focus on one or more skills and guide the inquiry process can be very effective as well (Kung & Linder, 2007). Whichever type of lab is used, in order to support strong scientific inquiry, all labs should incorporate the metacognitive skills of recognizing perspectives and background knowledge, finding strategies for applying, acquiring and communicating, planning the best procedure, and checking for errors. Furthermore, the vast majority labs should not be as simple as following a recipe, which is too often the case. When they are used, such labs should be augmented with other experiences to provide a broader representation of the nature of science, and are not effective on their own (Bakker & Akkerman, 2013; Wong et al., 2008). Within these designs, it is important to incorporate the time for students to reflect on their results, perspectives and actions, and to discuss these with groups. A clear presentation of the learning goals, useful reasoning strategies, and aspects of the nature of science is also necessary. Inclusion of these components into an appropriate structure will ensure a lab that is effective for practicing metacognitive and scientific inquiry skills.

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