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Teaching basic experimental design with an intelligent tutor

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Introduction

There is a broad international consensus that children's understanding of the principles and processes of basic experimental design – commonly known as the "Control of Variables Strategy" (CVS) – is an essential component of STEM education. For example, in the U.S., the recently published "Next Generation Science Standards"[1], recommends that, starting at "the earliest grades," students should learn how to "plan and conduct an investigation collaboratively to produce data to serve as the basis for evidence, using fair tests in which variables are controlled." The "National Curriculum"[2] for England includes a "statutory requirement" that "During grades 5 and 6 [ages 9-10 years], pupils should be taught…to plan different types of scientific enquiries to answer questions, including recognising and controlling variables where necessary" (p. 25). The curriculum further states that "'Working scientifically' will be developed further at key stages 3 and 4, [ages 12 –14 years] once pupils have built up sufficient understanding of science to engage meaningfully in more sophisticated discussion of experimental design and control" (p. 4). Mastery of the experimental method is included in South Korea's science standards [1] as well as Japan's national science standards [2]. And even though its fundamentals are not explicitly addressed by the German national science standards, CVS's underlying logic and procedures are characterized as crucial sub-skills of "experimental competence" [3]. Furthermore, both national and international assessments (e.g., TIMSS, PISA) invariably include several items assessing CVS-related skills and understanding.

A solid understanding of the causal reasoning that underlies unconfounded experiments is necessary for both the design and interpretation of their outcomes. This knowledge can also be applied well beyond the science classroom, for example when citizens attempt to understand and interpret correlational findings, such as those publicized in the media, often presented to support

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[1] http://www.nextgenscience.org/

[2] https://www.gov.uk/government/collections/national-curriculum

a particular public policy. Having this knowledge may help to protect citizens from uncritically accepting findings from correlational studies, or those containing confounds.

However, instructional research in the U.S. has repeatedly demonstrated that students – from third to seventh grade – have a surprisingly poor understanding of CVS [4 – 12]. Moreover, international assessments have consistently found poor performance on items that assess children's mastery of experimental process skills – including CVS. Consider, for example, two of the items that were on the open-ended TIMSS (2011) Grade 8 items[3] (Figures 1 and 2). For the item in Figure 1, only 14% of students (worldwide) provided the correct answer, with scores for individual countries ranging from 44% in Singapore to 2% in Indonesia. For the item in Figure 2, the average was 21%, with individual country scores ranging from 65% in Japan to 3% in Saudi Arabia.

Our own studies suggest that within-country variance on CVS skills (as well as much broader knowledge of scientific processes [13]) may be even greater than between-country variance. In one study conducted with students from a mid-sized metropolitan area in the mid-Atlantic region of the United States, we found extremely substantial SES-associated discrepancies in children's initial understanding of CVS, as well as in their post-instructional mastery rates in transferring any knowledge of CVS to other domains (13% and 62%, respectively)[4] [14]. SES-related differences in understanding of science-related skills such as CVS are very common in the USA. For example, Lorch *et al* [15] conducted a large-scale evaluation of various strategies for teaching CVS with nearly 800 students from 36 different fourth-grade classrooms in the state of Kentucky. Students were taught CVS through interactive classroom discussions. On a posttest requiring them to evaluate experiments, students in schools serving predominately lower-SES populations performed very poorly – only slightly above chance – and significantly worse than students in schools serving predominately higher-SES populations.

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[3] https://timssandpirls.bc.edu/timss2011/international-released-items.html

[4] Students' transfer performance was assessed on a 6-item test, in which students designed and evaluated (and, if necessary, corrected) an experiment in each of three different content domains (e.g., drink sales). Students achieved mastery performance by scoring at least 4 out of 6 on this test.

In our own research [15], analyses of the explanations students gave during remedial tutoring sessions about CVS revealed that lower-SES students were more likely to make characteristic mistakes and harbor robust schema-related misconceptions that interfered with their CVS learning. In particular, when challenged to design an unconfounded experiment that could isolate a causal factor, students would frequently, and incorrectly, interpret the question as asking them to achieve what Schauble, Klopfer and Raghavan [16] termed an "engineering goal" (producing a desired effect), rather than as a "science" goal (identifying causal factors). Students also expressed their beliefs about the effects of the domain-specific variables (e.g., "I think the steep ramp will make the ball go faster"); that is, students focused on the surface features of instruction rather than on the procedural and conceptual aspects of experimental design [17]. Moreover, we found that students interpreted "fair comparisons" or "fair tests" as those having *equivalent* conditions (i.e., where the two condition are set up exactly the same). We have no reason to believe that these types of deep misconceptions and misinterpretations – which can be quite robust – are unique to students in the United States. To the contrary, we suspect that they may be quite general challenges to effective CVS instruction, particularly among students who have little experience with science inquiry.

In contrast, what is predictive of students' ability to transfer their understanding of CVS to new domains is whether they are able to articulate the rationale for controlling variables (i.e., so that only the one variable under investigation can impact the results) [12, 18]. In another study [19], we had an experimental condition in which students' understanding of the rationale for controlling was supported by prompting them to indicate which non-focal variables could have caused a hypothetical difference in outcomes between conditions (i.e., we explicitly asked them to identify any potential confounds, or other variables that could have caused the outcome). These students showed better transfer performance than those students who did not receive these additional prompts. Thus, supporting students' explicit understanding of the rationale for controlling variables appears to be at least one way to produce a robust understanding of CVS.

Science inquiry support

Although CVS is fundamental to the scientific enterprise, it tends to be presented in science textbooks in a shallow manner. The short shrift given to CVS, *per se*, is exemplified in one widely-used 4th grade science text that allocates only 8 of its nearly 600 pages[5] to lessons about "the experimental method." Typically, only the *procedures* for designing experiments are explicitly taught in textbooks, while the *conceptual* basis for why those procedures are necessary and sufficient for causal inference is seldom addressed. For example, in Foresman's "Science" [20,21] middle school textbooks, experimental design is explained as: "Change one factor that may affect the outcome of an event while holding other factors constant." Nothing else is mentioned. Similarly, in the FAST curriculum textbook ("The Local Environment," [22]), experimental design is explained in the context of an experiment as: "This second group will be used for the control. What happens to the control is the basis for comparing effects." Again, nothing further is mentioned. Such brief statements about experimental design *procedures*, without subsequent instruction on the *rationale* for such designs, appear to be the norm, at least in the U.S. textbooks that we have examined.

Similarly, websites aimed at providing support to teachers who engage their students in experiment-based science inquiry (e.g., Science Buddies[6]; Discovery Education[7]) tend to briefly address procedures for conducting controlled experiments without further discussing the underlying rationale. For example, the popular Science Buddies[6] asserts: "It is important for your experiment to be a fair test. You conduct a fair test by making sure that you change only one factor at a time while keeping all other conditions the same." (Note the implicit use of "conditions" and "factors" as synonymous!) Similarly, the only explicit CVS instruction presented in a 21-minute video on the Scientific Method on the website Discovery Education[7] is simply: "Identify a single test variable and control other variables, so only one condition is being tested."

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[5] These pages "cover" the following topics: Classifying Plants and Animals, Energy From Plants; Ecosystems; Changes in Ecosystems; Systems of the Human Body; Water Cycle and Weather; Hurricanes and Tornadoes; Minerals and Rocks; Changes to the Earth's Surface; Using Natural Resources; Properties of Matter; Heat, Electricity and Magnetism; Sound and Light; Objects in Motion; Simple Machines; Earth's Cycles; Inner and Outer Planers; and Effects of Technology [22].

[6] https://www.sciencebuddies.org/science-fair-projects/science-fair/steps-of-the-scientific-method

[7] http://www.discoveryeducation.com/

Further, web-based materials for experiment-based science inquiry (e.g., Science Buddies; Discovery Education) generally fail to provide direct support for active student learning. That is, they don't include scaffolding for students as they set up their own experiments or provide feedback, even though such instructional actions have been shown to promote student learning [23 - 25]). Rather, most on-line websites that address experiment-based science inquiry offer pre-existing science projects that students can choose, accompanied by step-by-step instructions for doing a particular experiment (e.g., Science Buddies; education.com; The Lawrence Hall of Science[8]). Thus, students are not given the opportunity to design their own experiments and receive feedback on the quality of their experiments.

Some websites do include features that allow students to design experiments (e.g., biologycorner.com); however, they often do not provide feedback on the quality of the experimental design. PhET (phet.colorado.edu) is a popular website that provides various simulations of physical processes (e.g., alpha decay, pressure, electrical circuits) that students can manipulate to see how variables are inter-related; however, direct feedback on experimental design is not given. Going further, Inq-ITS (www.inqits.com) allows students to form hypotheses, design experiments, and virtually run experiments in given domains and draw conclusions. Although it does provide immediate feedback on some student actions, it does not provide automatic feedback on the experiments they design. Among the few publicly-available on-line websites that provide scaffolding and feedback to students as they engage in inquiry processes, WISE [26,27] does provide support for students' exploration of various science topics. However, the instructional emphasis is on conceptual learning and knowledge integration rather than domain-general experiment-based inquiry skills. In sum, we found no freely-available on-line programs or websites that supported middle school-aged students' active engagement when designing experiments that were also interactive – providing student-specific support, including feedback and scaffolding.

TED Tutor: Overview

Given (a) the centrality of CVS mastery to a large part of any curriculum that includes the experimental aspects of science, (b) the poor understanding of these concepts often found among

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[8] http://static.lawrencehallofscience.org/kidsite/. This site allows students to submit their results from various experiments and see how they compare to other students' results.

middle school students, including the array of alternative conceptions, misconceptions and misunderstandings of CVS instruction, and (c) the dearth of publicly-available on-line programs or websites that support active engagement with experimental design, we developed the TED Tutor (publicly available at: www.tedtutor.org). The TED Tutor (Figure 3) adapts instruction to individual students based on its assessments of their knowledge (including misconceptions) and ability, and provides students with continuous feedback on their actions.

Because the rationale for controlling variables is a relatively complex concept for middle school students, we hypothesized that students who are better able to integrate information (i.e., are able to make deductive inferences) would be better able to understand and articulate this rationale. In an analysis of log-file data that was generated by students using TED, we found that students' deductive reasoning achievement scores were highly predictive of whether students explicitly expressed an understanding of the rationale for controlling variables, which (as previously discussed) was in turn significantly related to students' CVS transfer performance [12]. Thus, in the TED Tutor, students' deductive reasoning is initially assessed (#1 of Figure 3) and can be used to determine the type of instruction they receive from TED.

After they complete the deductive reasoning test, students' initial understanding of CVS is assessed (#2-#3 of Figure 3). In the "Ramp pretest," in which students design an experiment for each of the four ramp variables, they are asked to indicate why they set up their experiment as they did by selecting responses from a series of drop-down menus, starting with their goal in setting up the experiment. This is intended to prompt explicit metacognitive reflection on what otherwise might be implicit goals.

Pathway 1 (higher-ability). Students who show a basic understanding of CVS (i.e., who at least contrasted the variable under investigation on the Ramp pretest) and/or better reasoning skills can be taken to the "baseline" instruction of TED (#7-#9 in Figure 3). In this baseline instruction, which is based on instruction given in Chen and Klahr [4], students evaluate three given experiments, and are given feedback on their responses. To promote their understanding of the rationale for controlling variables, they are asked if they could "tell for sure" that the focal variable caused a hypothetical difference in outcomes across conditions. To further reinforce their understanding of the rationale for controlling variables, they are asked whether each of the other (non-focal) variables could have caused the hypothetical outcome, and then they receive feedback on their responses.

Pathway 2 (lower-ability). Students who perform poorly on the CVS pretests and/or deductive reasoning test (#1)—and who therefore may be less able to follow the explanations given in the baseline instruction—are given a simplified, "step-by-step" version of the initial instruction. In this instruction, which is given before the baseline instruction, students are scaffolded in applying [the] three basic rules of CVS:

- R1: Identify the variable under investigation
- R2: Contrast that variable
- R3: Control/make same all other variables

Students' responses inform a Bayesian Knowledge Tracing engine, which determines how many rounds of questioning to give an individual student (#4-#6 and #10 of Figure 3). We have found that this simplified instruction supports students' understanding of the goal of the task as learning how to set up experiments that allow them to find out whether or not a variable affects an outcome. Students then progress to the baseline instruction for further instruction on the rationale for controlling variables and afterward set up experiments in the instructional domain ("Ramp posttest") and other domains ("Story posttest").

Effect of adaptive instruction for lower-reasoning students. We compared the effect of adding Pathway 2 to TED for lower-reasoning U.S. sixth- and seventh-grade students (i.e., student who scored low on the deductive reasoning pretest). As expected, the low-reasoning students performed significantly better on the transfer posttest when they were assigned to the more incremental Pathway 2 than higher-level Pathway 1. However, higher-reasoning students performed similarly in Pathway 1 and Pathway 2. In summary, adapting instruction to individual students' deductive reasoning skills led to better outcomes. In particular, the addition of the lower-ability pathway improved transfer outcomes among lower-reasoning students.

Policy Implications

As noted at the beginning of this chapter, understanding how to design and interpret experiments is an essential component of STEM literacy, and every K-12 science curriculum includes many opportunities for children to engage in the experimental process. Nevertheless, there is consistent evidence from national and international assessments that a solid grasp of the process and rationale underlying the creation, execution, and interpretation of informative experiments is exhibited by a scant proportion of the world's population. Thus, it is important to develop instructional procedures that will increase the likelihood that children will master both the procedural and conceptual aspects of CVS.

However, an oft-repeated critique of the number of substantive topic areas crammed into the K-12 science curriculum in the USA is that it is “a mile wide and an inch deep” [28]. But teachers attempting to convey the substantive knowledge base in their disciplines rarely have the luxury of devoting a full class (or two) to teaching the domain-general aspects of CVS procedures and concepts. Instead, at the beginning of a class devoted to some lab work associated with a particular topic, teachers typically introduce a brief overview (if any at all) about experimental procedures and concepts, but almost always in the domain-specific context of the particular topic being taught.

However, even though, as we noted earlier, instruction on CVS is rarely given adequate time, students’ understanding of it is invariably assessed on high-stakes tests. We created TED to address this problem. Our vision is that – prior to a lesson involving, for example, an experiment in electricity, or simple machines – teachers could direct students to TED’s on-line, user-friendly, adaptive and individualized instruction that would bring them “up to speed” with respect to the rudimentary conceptual and procedural aspects of a “good experiment.” Having completed this kind of domain-general, albeit limited, instruction, students would be in a much better position to really understand the steps and the reasoning that will enable them to obtain information and further develop domain-specific knowledge from their subsequent experiments about various topics.

As the next step in our research, we are embedding the TED tutor in a context in which children will be engaged in selecting a topic for, and then designing and implementing, an experiment to create a science fair project. This Inquiry Science Project Tutor (ISP Tutor) has both theoretical and applied aspects. The theoretical contribution will be to determine the extent to which presenting CVS instruction in the context of other inquiry activities elicits the type of skeptical scientific mindset that evokes a science goal, i.e., a goal of identifying causal factors, rather than an engineering goal: trying to achieve a specific outcome. From our earlier work, we expect the elicitation of science goals to lead to increased learning and transfer. The practical aspects will be to increase learning and transfer outcomes when TED instruction guides students in their design of unconfounded, albeit highly motivated, experiments. The ISP Tutor will provide support to students as they conduct inquiry activities about topics largely of their own choosing. We believe that this project is timely, given the accumulated findings of the importance of engaging students in such activities [29], as reflected in recent guidelines such as the U.S.'s K-12 Framework (2012) and NGSS (2013); England's National Curriculum (2014); Japan's Courses of Study (2008) [2], and Singapore's Science Curriculum Framework [31].

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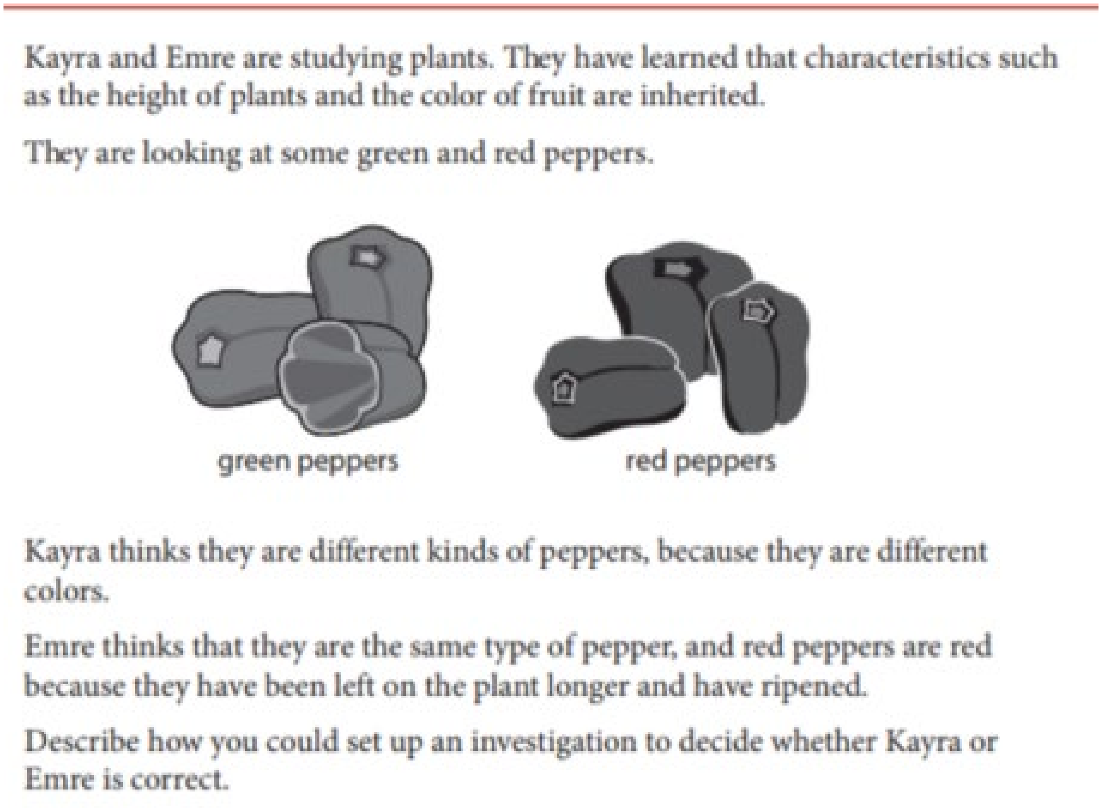
Figure Captions:

Figure 1. Released constructed response item (S042297) assessing Grade 8 students' experimentation skills from Trends in International Mathematics and Science Study (TIMSS) 2011. A correct response refers to either (a) planting (seeds from) green and red peppers AND observing the color of the fruit, or (b) planting (seeds from) green peppers AND observing if the fruit turns red. Example: "I would take one seed from each of the peppers and plant them under the same condition and at the same time. Observe them at the same time after the peppers start to grow. If the red peppers become red and the green peppers did not, this would show that the red and green peppers are a different kind."

Figure 2. Released constructed response item (S042238B) assessing Grade 8 students' experimentation skills from Trends in International Mathematics and Science Study (TIMSS) 2011. This item requires the student to notice – and correctly name – at least one of the following features that are the same in each "Setup": the temporal interval (2 minutes) and duration (10 minutes), the beakers (same shape, size, materials), the water (same volume, and type). Several other factors, unmentioned in the diagram or accompanying text are – presumably – also the same in each setup: the thermometer type, position for taking readings); the location and surrounding temperature of each setup.

Figure 3. Overall flow of TED Tutor, showing branching instructional event paths based on student responses to various assessment events.



Kayra and Emre are studying plants. They have learned that characteristics such as the height of plants and the color of fruit are inherited.

They are looking at some green and red peppers.

green peppers

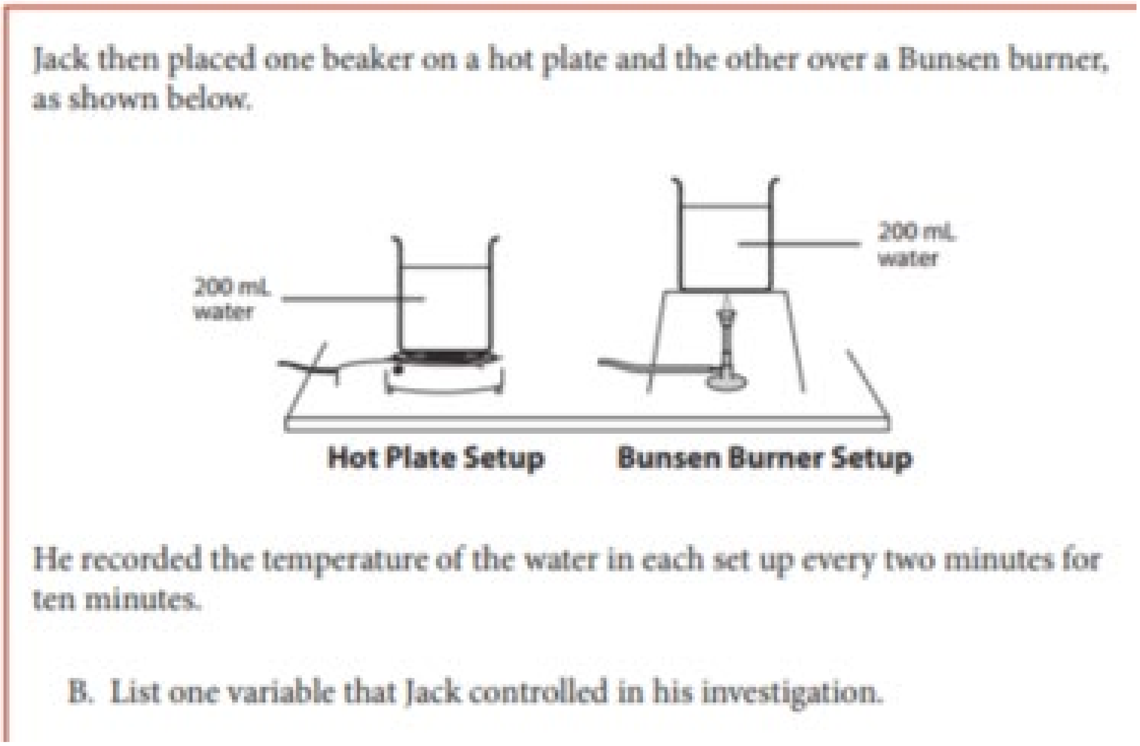
red peppers

Kayra thinks they are different kinds of peppers, because they are different colors.

Emre thinks that they are the same type of pepper, and red peppers are red because they have been left on the plant longer and have ripened.

Describe how you could set up an investigation to decide whether Kayra or Emre is correct.

Figure 1



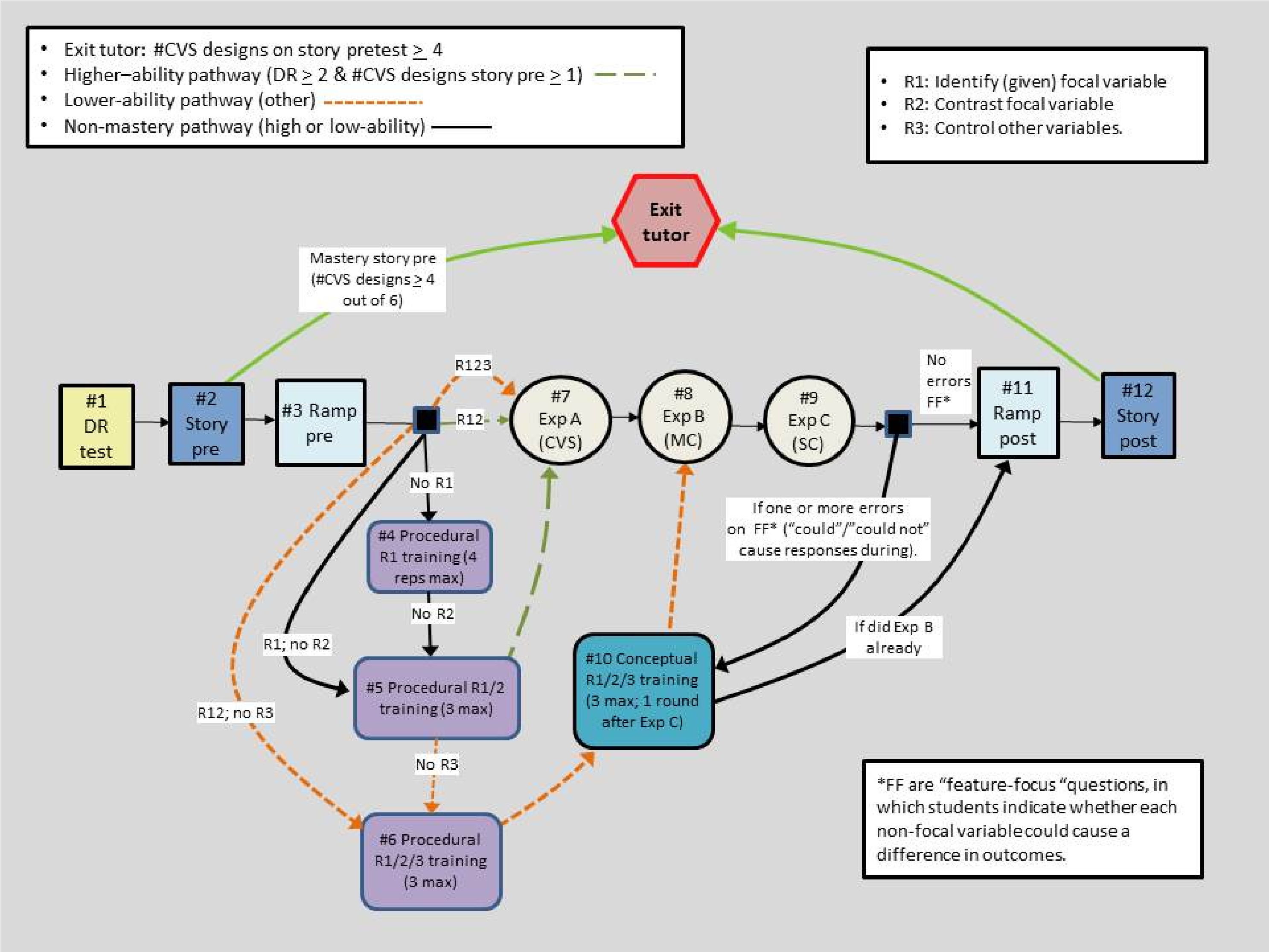
Jack then placed one beaker on a hot plate and the other over a Bunsen burner, as shown below.

He recorded the temperature of the water in each set up every two minutes for ten minutes.

B. List one variable that Jack controlled in his investigation.

Figure 2.

Figure 3.


Exit tutor: #CVS designs on story pretest ≥ 4
Higher–ability pathway (DR ≥ 2 & #CVS designs story pre ≥ 1)
Lower-ability pathway (other)
Non-mastery pathway (high or low-ability)
R1: Identify (given) focal variable
R2: Contrast focal variable
R3: Control other variables.
Exit tutor
Mastery story pre (#CVS designs ≥ 4 out of 6)
#1 DR test
#2 Story pre
#3 Ramp pre
R123
R12
#7 Exp A (CVS)
#8 Exp B (MC)
#9 Exp C (SC)
No errors FF*
#11 Ramp post
#12 Story post
No R1
#4 Procedural R1 training (4 reps max)
No R2
R1; no R2
#5 Procedural R1/2 training (3 max)
R12; no R3
No R3
#6 Procedural R1/2/3 training (3 max)
If one or more errors on FF* ("could"/"could not" cause responses during).
#10 Conceptual R1/2/3 training (3 max; 1 round after Exp C)
If did Exp B already
*FF are "feature-focus "questions, in which students indicate whether each non-focal variable could cause a difference in outcomes.