Conceptual Change When Learning Experimental Design

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As indicated by the other chapters in this volume, there are important cross-domain commonalities in conceptual change processes. However, some processes of conceptual change are specific to the domain in which those concepts are situated. In this chapter we describe several such processes that support changes in how children think about a small, but essential, domain-general, part of middle school science instruction: the design of simple experiments (typically dubbed the "Control of Variables Strategy" or "CVS"). Experimental design may be an interesting topic for conceptual change researchers because there are not only conceptual, but also procedural, aspects involved in its mastery.

Procedurally, CVS is a method for creating experiments in which a single contrast is made between experimental conditions. The procedure can be stated in a few simple rules. The experimental setup depicted in Figure 1 provides a referent: (a) Rule 1: identify the focal variable in a simple experiment (e.g., ramp height); (b) Rule 2: contrast values for the focal variable (e.g., a high ramp and a low ramp); (c) Rule 3: ensure that all non-focal variables (e.g., ball type, ramp surface, run length) are the same across conditions. Note that in the Figure 1 example, Rule 3 is violated: the experiment is completely confounded because all of the non-focal variables are set to different values.

Fig 1 about here

The simplicity of this rule set would seem to make it easy to teach and learn. However, this expectation is based on the assumption that students bring to bear "correct" conceptions of the purpose of experimentation: to identify the causal status of factors. If instead they bring different conceptions, instruction may not be so straightforward. In fact, this is precisely the situation that we address in this paper. Students' misconceptions about the goals of an experimentation task were reported by Schauble, Klopfer, and Raghavan (1991) who found that, rather than viewing the task as a way to identify a causal factor, many fifth- and sixth-grade children conceived of the goal of the task as producing desirable outcomes. Schauble et al. referred to these different views as "engineering goals" and "science goals," respectively. In our research aimed at constructing an intelligent tutor to teach experimentation skills (e.g., Siler, Klahr, Magaro, Willows, & Mowery, 2010), we have found the engineering approach to be common even in middle school children (e.g. Siler & Klahr, in press). Thus, learning CVS may involve a crucial conceptual transition from an engineering goal to a science goal orientation. Consequently, CVS learning may involve both conceptual *and* procedural change, processes that appear to be inter-related.

We begin this chapter by summarizing our research findings of CVS learning and goal misinterpretations to orient discussion of the nature of engineering vs. science goals in greater detail. Afterward, we consider possible underlying causes of goal misinterpretations. Although our work was not initially motivated by considerations of theories of conceptual change, the tenacity with which some students maintained their incorrect conceptions of the instructional task—which generally led to CVS learning failures—prompted us to take these into consideration. Thus, we examine students' conceptions of CVS vis-à-vis specific issues that arise in conceptual change research, including the nature of the conceptual change processes during CVS acquisition and evidence of "synthesizing" CVS procedures onto intuitive conceptual knowledge. Finally, we discuss the effectiveness of different instructional strategies for inducing conceptual change in light of the potential causes.

Research Overview

Our first investigation of CVS acquisition (Chen & Klahr, 1999) explored the effects of different levels of explicit instruction on the extent to which second- through fourth-graders were capable of learning CVS. Prior research suggested that children this age did not consistently apply CVS procedures (Bullock & Ziegler, 1999; Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Schauble, 1996). Several important findings emerged: (1) at least some third and fourth-grade students could, with some instruction, learn to consistently apply the principles of CVS, (2) providing students with explicit explanations rather than relying on them to discover the strategy on their own, produced better learning outcomes, and (3) even though children younger than what was previously thought were capable of learning CVS, there was still a developmental trend (i.e., second graders failed to learn CVS even when given explicit explanations and examples). When this explicit instruction was translated into a whole-classroom intervention (Toth, Klahr, & Chen, 2000), fourth-graders again demonstrated significant CVS gains. Moreover, learning from explicit instruction transferred to disparate domains (Klahr & Nigam, 2004; Matlen & Klahr, 2010), and over delays of up to three years (Strand-Cary & Klahr, 2008).

The studies summarized thus far were all conducted in schools serving middle- to high-SES populations. However, when delivered in a low-SES school, more intensive and individualized instruction was necessary for fifth- and sixth-grade students to achieve mastery rates comparable to those of the higher-SES students (Klahr & Li, 2005). In addition, whole-classroom instruction at two low-SES fifth-grade classrooms revealed that CVS mastery rates were less than half the mastery rate of a middle-SES student population (about 33% and 77%, respectively). Such results motivated our development of the "TED" (Training in Experimental Design) tutor, capable of adapting instruction to the needs of a diverse range of students.

Figs 2 – 7 about here

Study-1. In an initial evaluation of a non-adaptive version[1] of the TED-tutor, we compared learning and transfer rates of students from a school serving a primarily middle/high-SES and two schools serving predominately low-SES student populations. Students in the low-SES populations had significantly lower standardized test scores (notably, reading comprehension and science). Individual student-level data—including explanations—were collected throughout this evaluation, enabling the tracing of students' developing conceptual and procedural knowledge of CVS. Students first completed a story pretest, where they designed and evaluated experiments and explained their responses in three domains: drink sales, rocket design, and baking cookies (Figures 2 and 3). Students were then introduced to a virtual ramps apparatus and its four variables (Figure 4) and completed a ramps pretest (Figure 5) where they designed an experiment for each variable and explained their designs. Afterward, they viewed a brief video introduction to the lesson (Figure 6). During instruction (Figure 7), students evaluated three

[1] TED was constructed in several phases. Its earliest versions were non-adaptive, where the same material was presented to students regardless of their responses. Later versions include response-dependent instructional branching.

experiments and received feedback on their responses and explanations for why the experiments were (or were not) good ways to find out about the target variable; included was the rationale for applying CVS: that since only one variable differs, only *it* could cause a difference in the outcomes. Afterwards, students completed a ramps posttest, identical to the ramps pretest. The next day, they completed a story posttest (identical to the story pretest) that assessed their ability to transfer CVS to the three non-instructional domains. Three weeks later they completed the story posttest.

Again, the low-SES students performed somewhat worse on the ramps posttest than the higher-SES students. However, transfer mastery rates of the low-SES students were notably lower—only about one-quarter those of the higher-SES students. To investigate why, we examined the responses students gave throughout Study-1, during human-delivered remedial tutoring sessions of students in the whole-classroom study who failed to learn CVS from the classroom instruction, and story pretest responses of third-grade students from another investigation. We realized that students often interpreted assessment and instructional questions as asking them to (a) apply engineering goals of setting up experiments to produce a desired outcome (cf. Schauble et al., 1991), *or* (b) express their beliefs about the domain-specific variables, rather than as asking about the experimental design.

Table 1 about here

Age/SES-level and goal response. To provide more insight into possible causes of these misinterpretations, we first examine age- and SES-related trends in task interpretation then discuss the nature of these misinterpretations in more detail. Students' open-ended explanations on the story pretest were coded for goal expression/application. Typical student responses are shown in Table 1. Response patterns included those in which students' explanations indicated: (a) only engineering goals, (b) only science goals and/or CVS understanding, and (c) both goals. Procedure-only responses (e.g., "I made everything different") without explicit or implicit indication of intent were omitted from analyses (but frequencies are shown in the last two rows of Table 2). Responses indicating guessing or inability to explain were not considered to reflect any goal.

Table 2 about here

The goal response pattern of the middle/high-SES third-grade children (shown in the last column of Table 2) was significantly different from that of the middle/high-SES fifth-grade students'. Notably, the majority of the younger children (70%) applied only engineering goals on the pretest; 28% of the third-graders' responses indicated both science and engineering goals. The response patterns were also significantly different across SES levels (Table 2). The majority of students from the low-SES population (86%) *only* gave engineering goal explanations, whereas the majority of students from the middle/high-SES population (60%) indicated both goal types at least once throughout the story pretest.

However, the goal response pattern of the middle/high-SES third-grade students did not differ from that of the low-SES fifth-grade students. In general, developmental as well as SES-level trends were from application of only engineering goals across pretest problems to application of both science and engineering goals. Thus, science goals appear to strengthen and/or engineering goals weaken with both age and SES-level.

As noted earlier, tasks intended to activate science goals (to find out about causal factors) inadvertently but frequently activate engineering goals (e.g., Tschirgi, 1980; Kuhn & Phelps, 1982; Schauble, 1990; Schauble et al., 1991). We found that this tendency is rather tenacious: even *after* Study-1 students had (a) viewed a video introduction that explicitly stated that the goal of the lesson was to learn how to design good experiments, and (b) subsequently received explanatory feedback during instruction, many students held to their engineering goals (Siler & Klahr, in press).

Characteristics of Science vs. Engineering goals

Domain knowledge. What knowledge is involved in applying science vis-à-vis engineering goals? As previously discussed, students must understand the science goal underlying a task, or that the goal is to find out whether a variable is causal. Applying CVS in the service of the (science) goal requires identifying a variable to test, contrasting that variable's levels across conditions, and controlling other variables. CVS application within a particular domain does not depend on one's beliefs about the associated variable values. That is, any given non-focal variable can be set to any level (provided the levels are the same across conditions).

In settings where all relevant variables and their levels are explicitly defined, as is common in laboratory experiments (e.g., Chen & Klahr, 1999), and exploratory tasks (e.g., Schauble et al., 1991), it is *not* necessary to apply one's beliefs about the effects of variables[2]. And in fact, students rarely expressed their beliefs about variable effects within *any* type of science goal explanation (Siler & Klahr, in press).

As with science goals, engineering goals are context-general or applicable across various contexts and domains (e.g., making the fastest rocket or tastiest cookies). However, in contrast to CVS science-goal applications, the specific form an engineering goal takes often necessarily depends on one's beliefs about the problem's surface features, including the specific problem scenario and associated variables. For example, the application of an engineering goal of making the fastest rocket depends on the student's beliefs about which are the better levels for each variable. In contrast, if a student wants to *find out* whether the shape of the rocket matters by designing an experiment, her beliefs about the effects of the other variables are not relevant[3]. Three general types of engineering goals found in students' responses were "maximal-outcome," "same-outcomes," and "different-outcomes" goals (Siler & Klahr, in press).

By far the most common[4], "maximal-outcome" goals were those attempting to maximize an outcome, such as making the fastest rocket or selling the most drinks. For example, a fifth-grade student in Study-1 set up her drink stand at noon (rather than 3pm), selected an older child seller, and chose lemonade (rather than iced tea) because "…a lot of people are out earlier. I chose an older child because they can have more experience of selling stuff and I like lemonade." As shown in this example, applying maximal-outcome goals requires tailoring the design to one's beliefs about the relevant variables—specifically, beliefs about which variable values are better for producing an outcome.

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[2] However, conducting an experiment in the real world, where one cannot control every possible variable, requires identifying and controlling those variables one believes might affect the outcome.

[3] Assuming no interactions among variables and that none of the levels contribute to floor/ceiling effects.

[4] Maximal-outcome responses accounted for 96% of middle/high-SES and 88% of low-SES students' engineering responses on the first story pretest item (Siler & Klahr, in press).

Less common were "same-outcome" goals such as producing equally-fast rockets or similar-tasting cookies. For example, another fifth-grade Study-1 student evaluated a non-contrastive design (where the values for each variable were the same across conditions) as good because: "if they have the same ingredients they might have the same taste." Same-outcome goals may be related to children's intuitive notions of fairness (e.g., Wollman, 1977), and were primarily found when students were asked whether a given design was a "fair way" to find out about the focal variable in the whole-classroom study. Producing the same outcomes can be done either by setting all variables the same across conditions or by "balancing" variable values so that the variable effects "cancel each other" (e.g., by selecting the "better" value for variable1 of condition1 and the "better" value for variable2 in condition2).

The third general type of engineering goals identified were "different-outcome" goals—intentions to make outcomes differ across conditions, such as making one rocket fly faster than another or selling more drinks at one stand than another. For example, Study-1 students frequently evaluated the unconfounded experimental design testing the effect of the number of windows on a rocket's flight as "Bad" because (as one student explained) "windows would not make a difference." This goal type may be related to a notion that only experiments showing that a variable (or variables) has an effect are good experiments, perhaps because this is a more "exciting" outcome. Applying a different-outcome goal may require application of beliefs about variable effects, when, for example, students contrast just those variables believed to be causal or use what they believe to be the better variable values in one condition and other values in another.

The last two types of engineering goals also demonstrate the link between students' conceptual knowledge—or understandings of "fairness" and perhaps what "good" experiments produce—and their procedural applications. That is, "fairness" interpretations typically led to non-contrastive designs and misunderstandings of the purpose of experiments were related to contrastive designs.

Goal explicitness. An important feature of students' science goal responses is that they usually included explicit statements of intention; phrases expressing explicit science goals are underlined in Table 1. However, when students applied engineering goals, they rarely *explicitly* stated the corresponding intention of producing a specific outcome (e.g., “I am trying to make the fastest rockets.”); rather, they tended to state their beliefs about the problem-specific variable values. For example, students generally did not explicitly state that they were trying to sell the most drinks. Rather, they tended to allude to the positive effects of the variable values they selected with respect to a desired outcome. In the drinks stand example in Table 1, the student explained that she chose noon because it is “the hottest time of day” (and people would be thirstier and buy more drinks) and chose an older child seller because “older kids [usually] know how to talk better” (and are better at persuading people to buy drinks).

Table 1 about here

Procedural-conceptual relationships. When students expressed science goals, they almost always contrasted the variable(s) they were trying to find out about (Siler & Klahr, in press). Thus, science goals appear to be tightly linked to contrasting variables. Although the most common maximal-outcome goals were not associated with particular designs, different-outcome and same-outcome goals were generally associated with non-contrastive and contrastive designs (respectively).

In summary, (a) students’ science goal applications appear to be dissociated from—whereas engineering goal applications are generally associated with—domain-specific beliefs (b) students’ intentions within science goals appear to be explicit, whereas intentions within engineering goals may be implicit, and (c) science goal orientations appear to be more strongly associated with procedural aspects (i.e., contrasting variables) than engineering orientations.

Causes of Goal Misapplications

Why do students—especially younger and low-SES students—adopt engineering goals? One possibility is that students associate “experimenting” with achieving dramatic or exciting outcomes (Schauble et al., 1991). At the very least, students this age—and older—typically hold unsophisticated views of experimentation that include elements of both engineering and very basic science approaches; for example, they typically view the purpose of experiments “as producing a desirable outcome or a new fact” (Smith, Maclin, Houghton, & Hennessey, 2000). However, when references to “experiment” were removed from the story pretest[5], which students completed in non-science classrooms, almost half (45%) of low-SES fifth-grade students still gave engineering or variable-effects responses on the first item compared to 53% of low-SES fifth-grade students from the same schools who answered the original story pretest referencing “experiments” in their science classrooms. Furthermore, in a recent study comparing instruction that referenced “experimenting” with the same instruction that did not (i.e., it was framed in terms of “solving brain teasers”), students in the “experiment” framing condition were *not* significantly more likely to indicate engineering (or “variable effects”) misinterpretations than students in the “brain teaser” framing condition on their first instructional responses (22% vs. 43%, respectively). Thus, context-rich problem scenarios appear sufficient for triggering engineering goals.

Another possibility is that students are unable to apply basic science goals. However, several studies have demonstrated that even young children apply science goals in certain scenarios. For example, Sodian, Zaitchik, and Carey (1991) found that first- and second-graders can differentiate between engineering and science goal applications in simple tasks. That is, when children were presented with the problem of figuring out which of two doors—a large or a small one—would be better for determining whether a large or small mouse was stealing food, the majority of children chose the small door, correctly reasoning that, if the food was stolen, it had to be due to the small mouse because a larger mouse could not fit through the small door. However, when asked to ensure that the mouse—whatever its size—could get to the food, these children correctly chose the large door. Children are also able to solve similar tasks (Klahr & Chen, 2003), and other research has suggested that preschoolers can apply science goals to identify causal variables (Gopnik, Sobel, Shulz, & Glymour, 2001).

So why were the younger and lower-SES students in our studies less likely to apply science goals? One possibility is that children may not be aware of the hypothetical nature of their beliefs (Vosniadou, Vamvakoussi, & Skopeliti, 2008); thus, when they read problem statements involving

[5] For example: “design an experiment to test for whether or not the time of day makes a difference in how much is sold” was reworded as: “figure out a way to find out whether or not the time of day…”

familiar scenarios with associated outcomes, they may not realize that their beliefs about how the variables affect the outcomes may be wrong. And if so, they are unlikely to adopt science goals—after all, it does not make sense to investigate what one (thinks one) already knows.

Dual-process models of cognition (cf. Kahneman, 2003), hypothesizing the relationship between automatic, intuitive, associative processing—including belief elicitation—and more effortful, logic-based problem-solving and monitoring processes, may further shed light on this question. In some dual-process models, these processes are assumed to run in parallel (e.g., Epstein, 1994; Sloman, 1996) and in others (e.g., Kahneman & Frederick, 2002; Evans, 2006), serially. In parallel accounts, because associative processes are faster, they generally "win the race" to consciousness even if a certain scenario also triggers higher-level reasoning processes. And, if accepted by conscious monitoring processes, this output will be applied. In serial accounts, intuitive processes are first activated and their resulting judgments are evaluated. If deemed inadequate, higher-level processing will step in. In yet another account of dual-processing (De Neys, 2012), monitoring results from the comparison of two competing *intuitive* outputs. Only when conflicts in these outputs are detected are higher-level processes enacted.

Thus, common to all models is the monitoring/evaluating of products of intuitive processing. Because some metacognitive skills have been linked to reading comprehension (e.g., Kolic-Vehovec & Bajanski, 2007) and higher-SES students' reading comprehension scores were significantly higher than lower-SES students', the higher-SES students likely had better metacognitive/monitoring skills. Thus, metacognitive differences may have been one cause of the differences in goal-related and CVS learning.

However, this monitoring may normally be lax (Kahneman, 2003), requiring sufficiently salient cues to be triggered. On the 6-item story pretest, for each of the three domains, students were first asked to design an experiment for a given focal variable before evaluating a set-up in that same domain with the same variables. Because surface features were the same in the design-evaluate question pairs, one may expect other problem features—including cues to the science-goal nature—to become relatively more salient in the second (evaluate) item. Study-1 students were in fact significantly more likely to express science goals on the second items of question pairs. Reading achievement (a proxy for monitoring skill) and science scores were equally predictive of science-goal application on the second (evaluate) items. In contrast, only students' science achievement scores were related to science-goal expression on the first (design) items. These results suggest that general science knowledge—and likely science goal strength—is a factor regardless of cue strength, and metacognitive skills play a greater role as cue salience increases. However, further research addressing these issues is warranted.

However, students did not take more time to formulate responses when they applied (non-CVS) science goals than engineering goals on the first story pretest item, which may suggest these applications involve the same—likely intuitive—processes. With one exception, students who expressed science goals designed maximally-confounded comparisons; thus, contrasting all variables may be a common default heuristic. However, once students understand the task in the context of a science-goal framework, we believe that the more effortful, logical thinking comes into play when learning to control variables. Consistently, Study-1 students took significantly more time when they designed their first unconfounded set-up than on the previous question (when they designed confounded comparisons) of the ramps pretest.

The Nature of CVS Development

Procedural development. A common theoretical account of conceptual change is that conceptual knowledge often develops incrementally and intentionally (Vosniadou et al., 2008). Can such additive enrichment mechanisms—in which new information is incrementally integrated with existing knowledge—account for the development of a procedural knowledge structure such as CVS? It is also conceivable that students could—in "aha!" moments—come to realize the necessity of applying CVS – perhaps by realizing its underlying logic (cf. Posner et al., 1982). To address this question, the ramps pretest responses of Study-1 students—in conjunction with their experimental designs—were coded for expression of CVS rules (explicated earlier). For example, responses in which students expressed the intention of testing the given focal variable, but did not contrast the focal variable were coded as R1-only. But if the focal variable had been contrasted in the design, this response would have been credited as R1 and R2. Coding categories, in order of approaching a complete CVS explanation, are shown in Table 3.

Table 3 about here

Table 4 shows the distribution of the different types of student responses from the first to second ramps pretest question. For example, the first data cell in the table shows that eight students who gave an engineering response to the first question also gave one to the second questions, and (farther down in the table) that five of the children who gave CVS responses on Q1 also did so on Q2. An incremental response pattern would correspond to fewer "hits" in cells as one moves farther from the diagonal (highlighted cells—which indicate consecutive responses at about the same level of sophistication). The modal response was to remain within a category. For example, 8 of the 14 students who gave engineering responses on Q1 of the ramps pretest also gave engineering responses on Q2. The highlighted cells in Table 4 represent responses to Q1 and Q2 at roughly the same level of sophistication (e.g., comparing, testing multiple variables, and contrasting variables are approximately the same knowledge state). Response pairs to the right of the highlighted cells show Q2 responses that are progressively more sophisticated than the Q1 response (i.e., show knowledge of more CVS rules).

The student with the largest knowledge advancement could not explain his/her Q1 set-up (and was assigned a "Don't Know" response) but on Q2 gave a CVS (procedure-only) response. Thus, this student appeared to suddenly "get" CVS. However, s/he expressed an understanding of the need to compare conditions on the story pretest (and showed implicit understanding of CVS procedure on Q3 and Q4 of the story pretest), so this "leap" in knowledge development during the ramps pretest is not as large as it appears. Overall, only 6% of students advanced more than one CVS rule between Q1and Q2. Of students whose explanations became more sophisticated, 75% advanced no more than one rule. Thus, for the majority of Study-1 students, procedural knowledge of CVS developed incrementally when students designed experiments in the absence of feedback. That is, as shown in Figure 8, smaller advances were more common than larger ones, which were increasingly rare.

Table 4 about here

Figure 8 about here

Understanding CVS logic. Although students' CVS procedural knowledge seemed to develop incrementally, was there evidence of "aha!" moments—insights in which students understood the logic of

CVS (i.e., that only the focal variable should be contrasted so only it can affect the outcome)? In Study-1, only eight students expressed the logic of CVS on either the story or ramps pretest. Four of these students expressed the logic of CVS only *after* expressing the full CVS procedure (i.e., that only the focal variable should be different). The remaining four students expressed an understanding of the logic of CVS very early—on the first or second question of the story pretest. These students may have experienced “aha!” moments, but, because these occurred very early in the pretesting, it seems more likely they were instead recalling previously developed knowledge.

Synthesizing conceptual and procedural knowledge. As with conceptual change found in other domains (e.g., Vosniadou & Brewer, 1992), there was evidence that some students additively built onto their intuitive engineering frameworks or “synthesized” new information (i.e., CVS rules) with their engineering goal schemas. However, such evidence was sparse, suggesting that engineering frameworks impeded procedural learning.

One example of synthesizing procedural rules onto an existing intuitive conceptual framework comes from a low-SES sixth-grade student during a remedial tutoring session following whole-class instruction in which this student had developed a “same-outcomes” misinterpretation. In tutoring, the student learned to contrast the focal variable. When asked to design a comparison to find out if the surface [of the ramp] affects how far balls roll, he set the first ramp to steep, with a rough surface, and the ball starting at the top of the ramp. He set the other ramp to steep, but with a smooth surface and the ball starting in the middle. Thus, this student correctly contrasted the focal variable (the ramp surface). When asked why he chose to use different starting positions, he responded: “Because the rough one [inaudible] probably mess the ball up, so I made it longer so it could move faster.” When asked if he was trying to make one of the balls “beat the other,” he responded: “No, I’m saying that if it’s rough and then it’s [at the top], [I want] to see if the [middle] and smooth one could get down there at the same time, because the heights will make the ball roll faster, and this one’s smooth so it can roll down without messing up.” Thus, he maintained his initial same-outcomes goal by varying the starting positions as well as the focal variable, so that the rough surface (which he believed would slow the ball) was paired with the top starting position (which he believed would make it roll faster), and the smooth surface was paired with the middle starting position.

As discussed in Siler and Klahr (in press), students sometimes—though rarely[6]—indicated both engineering and science goals when referencing a particular set-up. For example, one low-SES fifth-grade student explained her ramps design as follows: “I thought that you should use steep because if it was flat it wouldn’t be able to roll that well. I don’t know why I used fim and sif, I just thought it would work. I picked the middle because it’s a shorter distance and it might roll farther. And I picked the top to see if it might roll farther than the middle.” This student expressed a science goal for the focal variable (starting position) after explaining her engineering-based decisions for the other variable settings. Thus, students occasionally incorporated both engineering and science goal perspectives within a single problem, without noticing the conflicting goals.

Strategies for Inducing Conceptual Change in CVS

Explicit instruction. As discussed in the introduction, the CVS instruction given in previous studies (e.g., Chen & Klahr, 1999; Strand-Cary & Klahr, 2008; Matlen & Klahr, 2010) has led to high rates of CVS adoption and transfer for older and higher-SES students. As previously shown, these students were more likely to adopt science goal orientations during pretesting. Thus, instruction that includes explicit explanations of the procedural and logical aspects of CVS seems appropriate for students likely to interpret instruction within science goal frameworks. This is further supported by a recent study (Siler, Klahr, & Price, under review) finding that, for seventh-graders who expressed science goals on the final story pretest item, immediately entering instruction was more beneficial than completing a ramps pretest prior to entering the instruction (abbreviated to control for time on task)[7].

Eliciting science goals.

Via novel variable values. We have suggested that (a) children misinterpret the task goal because surface features activate engineering goals, and (b) misinterpretations are maintained when metacognitive

[6] For example, only 4% of responses indicated both goal types on the first question of the ramps pretest.

[7] This trend was reversed for students who did not express science goals on the final story pretest item.

processes fail to detect them. To investigate the extent to which students monitor their understanding, we examined the effect of presenting children variables with both familiar and unfamiliar levels. If students monitor their understanding, they should be more likely to apply science goals for the former variables.

On the ramps pretest, students were asked to design one experiment for each of the four ramps variables: (Q1) the starting position, (Q2) the surface, (Q3) the ball type, and (Q4) the slope. Two of these variables had commonly-designated value names (i.e., the slope could be steep or not steep, and the starting position of the ball could be at the top or middle of the ramp). Two variables were given made-up value names (i.e., ball type was either "bab" or "lof," and the ramp surface either "sif" or "fim"). Students were *not* more likely to express science goals on questions asking them to test variables with unfamiliar values (Q2 and Q3) than on questions asking them to design experiments to test variables with familiar values (Q1 and Q4). Thus, merely presenting students with variables that had unfamiliar values did not promote shifting from engineering to science goals for fifth-grade students.

The failure to elicit science goals this way was partly due to students making assumptions about the made-up variable values' effects. For example, one low-SES Study-1 student assumed that the surfaces differed: "It has an easier surface for [ramp 1] and harder for the other," even though the surfaces differed only in color. This student also mistakenly perceived a difference in the shapes of the (actually identical) balls: "[Bab's] shape is rounder than [lof's]." Another (low-SES) student stated: "I was thinking that sif is probably fatter than fim" when explaining her design decision. These results support poor metacognitive skills as a factor in engineering goal applications, and correspondingly, the insufficiency of using unfamiliar variable levels to induce goal shifting.

Via explicating beliefs and goals. As discussed previously and illustrated in the last section, students are often "not aware of the hypothetical nature of their beliefs" and "presuppositions that constrain their learning and reasoning" (Vosniadou et al., 2008, *p*. xviii). This may also apply in the case of goal shifting, where students may not be aware of the hypothetical—and possibly wrong—nature of their assumptions about variable effects underlying their engineering designs. In addition, they may not even be aware they are applying engineering goals. As noted earlier, students rarely *explicitly* stated engineering intentions when explaining their set-up choices. Would providing explicit feedback following students' engineering goal selections (on the ramps pretest) promote metacognitive awareness and improve subsequent learning?

To address this question, sixth-grade students were assigned to one of the following conditions: (a) no feedback, (b) science goal feedback, or (c) "both-goal" feedback. In the science goal feedback condition, students were reminded of the ramps pretest task goal—to design an experiment to test whether the focal variable affects how far the balls roll—and that the task was not to make the balls roll "farther, faster, or the same." Students were reminded of the general goal of experiments—to find out whether something makes a difference—and told that they would be learning how to design experiments to see whether the different parts of the ramps make a difference.

In the both-goal feedback condition, students heard the same explanations as in the science goal feedback condition. In addition, they were told that the point of an experiment was *not* to try to make a certain result, but instead to find out whether something makes a difference. Students were also told: "If you are setting up the ramps to make something you want happen, you may be using your ideas about how the different parts of the ramps work. However, you could be wrong about how the parts of the ramps work if you haven't tested the parts first. So, in order to test the parts correctly, you must NOT assume that you know how any of the parts work." Finally, as in the science goal feedback condition, students were told that the goal of the lesson was learning how to design experiments to see whether the different parts of the ramps work. In both feedback conditions, visuals including key points presented textually and depictions of the ramps accompanied the audio presentation.

The effects of this manipulation were modest, at best. Students in the both-goal condition answered slightly more of the multiple-choice questions asked during the instruction correctly than students who received no feedback, and tended to answer more questions correctly than the "science goal" condition students (but this difference was not significant). Although students in the both-goal condition also tended to design more unconfounded experiments on the ramps posttest than students in the other conditions, there were no significant pair-wise differences. Nor were there any differences on the immediate or delayed posttests. There were signs of an initial positive effect of feedback addressing both students' incorrectly-applied engineering goal and the relevant task goal, but this effect faded in time. This suggests that students may require more time and support to understand or realize the nature of their underlying assumptions and goals in the context of CVS instruction.

In summary, stronger interventions than the two just discussed may be necessary to induce the metacognitive processes that cause goal shifting. For example, in a task in which students were explicitly given relevant problem variables, their levels, and target outcomes by the experimenter, Schauble et al. (1991) found that fifth- and sixth-grade children from a middle-SES population shifted from engineering to science goals when the outcomes of their experiments contradicted their expectations. Thus, showing students experimental outcomes that contradict their expectations may be one such intervention that can successfully promote goal shifting in younger and lower-SES children.

Another possibility, in line with Vosniadou et al.'s (2008) recommendation, is to engage students in full-class discussions with the aim of promoting goal revision. According to Vosniadou et al., such engagement "ensures that students understand the need to revise their beliefs deeply instead of engaging in local repairs" and supports students as they "engage in the conscious and deliberate belief revision required for conceptual change" (Vosniadou, et al., 2008, p. 27). Alternatively, strengthening students' science goal frameworks likely will induce goal shifting.

Via activating intuitive science-goal knowledge. Vosniadou et al. (2008) suggested promoting conceptual change by building on students' intuitive ideas. As discussed previously, even young children do seem to have an intuitive notion of "comparing and contrasting" variable levels to see whether it affects an outcome (cf. Gopnik, Sobel, Shulz, & Glymour, 2001). Thus, building on this conception may activate students' science goals (and subsequently aid procedural CVS development). After the story pretest, as students were introduced to the ramps pretest, they were told: "In an experiment, we compare things to see if they affect the result. We need two ramps in order to do an experiment because we need to compare and contrast how far the two balls roll." If eliciting students' idea of comparing and contrasting does elicit science goals, we would expect to see a jump in science goal application between the final question of the story pretest and the first ramps pretest item. And, in fact, there was a jump in the likelihood of expressing science goals between the final design item of the story-problems pretest and the first ramps pretest item (Figure 9) for the three fifth-grade classrooms who participated in Study-1. In contrast, the rates of science goal expression were stable within the story-problems and ramps pretests.

Fig 9 about here

Furthermore, of students who applied engineering goals on the final story pretest question, over half (56%) expressed science goals on the first ramps pretest item. Of students who *only* applied engineering goals throughout the story-problems pretest, almost half (41%) expressed science goals for the first ramps pretest item. There were no differences in the likelihood of transitioning to science goals across the three classrooms in either case. Thus, eliciting students' intuitive understanding of "comparing and contrasting" variable levels in the service of a science goal appeared to promote goal shifting for about half of students who appeared to be "stuck" within engineering frameworks, regardless of SES-level. In summary, means of inducing goal shifting that involved eliciting conceptual knowledge associated with science goals appear to be more effective than those attempting to promote metacognitive awareness.

Discussion

In this chapter, we discussed the nature of students' beliefs related to experimental design, how these beliefs change as students answer questions about experimental design, and how students may be supported in coming to understand this topic. Our central interest has been the extent to which the same processes that are associated with belief revision in primarily conceptual domains—that is, when students learn about the form or function of existing entities (e.g., the earth and solar system)—can also account for the ways in which children learn this skill, which includes both procedural and conceptual components. While many other domains are rich with both procedural and conceptual knowledge, most studies of conceptual change have focused on learning of the latter knowledge type. Few have focused on how procedural and conceptual knowledge interact. In this chapter, we showed how learning of procedural skills is intimately related to the learner's conceptual understanding—their conceptualization of the task goal.

Overall, there appear to be two types of conceptual change relevant to learning CVS: belief revision and categorical shifting (cf. Chi, 2008). If children adopt science goals, then their learning of CVS resembles the type of intentional knowledge development characteristic of belief revision found in conceptual domains. That is, children appear to develop their understanding of CVS incrementally—or one CVS rule at a time—rather than holistically. An understanding of the underlying rationale for applying CVS—at least in its explicit form—appears to develop after the formation of a procedural understanding.

However, some children—especially younger and lower-SES—appeared to interpret pre-instructional questions asking them to design and evaluate experiments within engineering frameworks. If this orientation continues into instruction, students may either develop synthetic models or, more typically, fail to learn anything. Thus, conceptual change relevant to learning CVS involves "switching" from engineering to science goal orientations. We believe this type of conceptual change involves a type of category shifting, where children must reconceptualize the task goal from achieving an optimal outcome to creating a way to find out about variable effects. Because students in late elementary to early middle school (when CVS is typically taught) likely already have basic knowledge structures associated with pursuing science goals (cf. Sodian et al., 1991), we believe it is more a matter of eliciting this knowledge than developing it. In fact, when students were presented with the (basic science goal) notion of "comparing and contrasting" across conditions, science goal expressions increased. In addition, the relative rarity of developing synthetic models of CVS—in which students synthesize CVS rules onto their intuitive engineering frameworks—may be a consequence of the availability of both engineering and the target science frameworks. That is, the very rules students are learning (i.e., contrast the focal variable) may trigger the activation of basic science goals, rendering synthetic models uncommon. This contrasts with category shifting conceptual change in other domains where even a minimal target framework is unlikely to be (as) available, such as when learning emergent processes (Chi, 2005). Synthetic models may be more common in such circumstances.

We suggested that the dual-process theory may illuminate the goal-shifting aspect of conceptual change in CVS. In dual process models of cognition (cf. Kahneman, 2003; Stanovich & West, 2000), two general types of cognitive processing occur: (a) “intuitive” associative processes that are activated by highly accessible stimuli, and (b) “slower, serial, effortful” reasoning processes that are “more likely to be consciously monitored and deliberately controlled” (Kahneman, 2003, *p*. 698).

These models predict what was found here: that students with poorer self-monitoring skills—including younger and lower-SES students—would be more likely to apply engineering goals. Because monitoring processes are typically lax even in adults (Kahneman, 2003), stronger cues to the correct nature of the task may be necessary for its detection. Because habituation should render surface features less salient, we expected monitoring to play a greater role in detecting the science goal nature of the task in the second questions of each domain on the story posttest. In fact, a measure of monitoring skill, standardized reading comprehension scores, along with science achievement scores, was correlated with goal expression on the second questions. However, on the first items in each domain, only students’ science achievement scores were related to science goal expressions. Thus, students’ conceptual knowledge may be even more vital when cue salience is low.

That some students possessed weaker metacognitive skills is further suggested by their confident—though unwarranted—assumptions about effects of completely novel variable levels. Weaker monitoring skills, too, may have been responsible for failures of interventions targeting these skills to promote conceptual change. Eliciting science-goal related knowledge appears more fruitful for promoting conceptual change; however, our findings also point to the need to improve metacognitive skills in these student populations.

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Table 1. Examples of science and engineering goal expressions by problem scenario.

Problem scenario	Science goal response	Engineering goal response
Drink stands (Q1&2)	"I picked different [stands] so I could see which one did better." "I set them up the way I did because now I can compare them."	"The hottest time of day is noon. And usually older kids know how to talk better." "At three o'clock [k]ids will be out of school and thirsty for some ice cold lemonade and … noon all the kids would be in school so they could not leave and get lemonade."
Rocket ships (Q3&4)	"To see the differences and the different height how high it goes." "I set it up this way so I could see what engine, way the ship was made, and the windows had an [e]ffect on the ship's flight"	"I did the curved body because the air will go right by it and the straight engines will make it go straight up." "because if it is str[a]ight it will fly str[a]ight and if the engine is down it will blow the rocket into the air"
Cookies (Q5&6)	"I set it up to see who likes better cookies." "I did this so that I could compare the experiments by putting the first two items down that were the same, but the number of eggs diff[e]rent so that I could see if the number of eggs affected how the people liked the cookies."	"The honey might not melt a lot as the sugar and three eggs and 350 degrees because 350 is a high temperature." "I set it up because 200 degrees would be to[o] low and 500 degrees would be to[o] high. 3 eggs would probably be to[o] much egg and alot of people like sugar on there [sic] cookie"

Table 2. Pretest goal student response pattern frequency (and percent) by SES-level and grade.

SES level	Low	Mid/High	Mid/High
Grade	5	5	3
Science-only	0 (0%; *0%*)	6 (14%; *13%*)	1 (2%; *1%*)
Engineering-only	18 (86%; *60%)*	11 (26%; *23%*)	37 (70%; *52%*)
Science & Engineering	3 (14%; *10%*)	25 (60%; *52%*)	15 (28%; *21%*)
Science & procedure	*1 (na; 3%)*	*0 (na; 0%)*	*1 (na; 1%)*
Engineering & procedure	*8 (na; 27%)*	*6 (na; 13%)*	*17 (na; 24%)*
Procedure-*only*	*0 (na; 0%)*	*0 (na; 0%)*	*2 (na; 3%)*
Total	21 (*30*)	42 (*48*)	53 *(73)*

Table 3. Explanations for ramps designs ordered by number of CVS rules expressed.

Response type	**Example (focal variable is starting position)**	**CVS rules**
Engineering (ENG)	"I made them so the balls will roll fast."	None
Variable effect (VE)	"I think the shorter one will win."	None
Don't know (DK)	"I just guessed."	None
Science only (no rules)	"I designed it the way I did so I could see what happens."	None (Science only)
R1: Identify the focal variable.	"I wanted to find out about the starting position." (but starting positions are not contrasted)	R1 only
R2: Contrast the variable(s) one is testing.	"I wanted to see if the starting position and slope make a difference." (starting positions and slopes are contrasted)	R2 only
R3: Control the variable(s) one is not testing.	"The balls and slopes should be the same."	R3 only
R1/2: Contrast the focal variable.	"I did it because the balls are in different places."	R1 and R2
CVS	"Only the starting positions are different."	R1, R2, and R3
CVS + Logic (CVSL)	"Only the starting positions are different, so only they could make one ball roll farther."	R1, R2, and R3 + Why control

Table 4. Per-student frequency: response to Q1 vs. Q2 on ramps pretest.

		Ramps pretest Question 2 response													
		…No CVS rules or goal…			Goal only	…………One CVS rule……….				Two CVS rules		Three CVS ……rules……			
		ENG	VE	DK	SCI	SCI-R1	TMV	R2	R3	R2/R3	R1/R2	CVS	CVSL		Row total
Ramps pretest Question 1 response	ENG	**8**	2	2	1		1							ENG	14
	VE	1												VE	1
	DK	1		**1**				1			1	(1)		DK	5
	SCI	2	1	1	**3**					1				SCI	8
	COMP		2		1						1			COMP	4
	TMV	1												TMV	1
	R2			2		1	1	**7**	2	1	6	1		R2	21
	R1/2	1									**1**	2		R1/2	4
	CVS				1						1	**5**		CVS	7
	CVSL												1	CVSL	1
	Total	14	5	6	6	1	2	8	2	2	10	9	1		66

Figure Captions

Figure 1. Depiction of ramps apparatus used in previous studies.

Figure 2. Screenshot of an experimental design question from the story pretest given in the TED-tutor.

Figure 3. Screenshot of an experimental evaluation question from the story pretest.

Figure 4. Screenshot of the introduction to the ramps apparatus.

Figure 5. Screenshot of the ramps pre/posttest segment of the TED-tutor.

Figure 6. Screenshot of video introduction to the lesson.

Figure 7. Screenshot of interactive instruction given in the TED-tutor.

Figure 8. Frequency of the difference in number of CVS rules expressed from Q1 to Q2 on the ramps pretest.

Figure 9. Percentage of science goal responses expressed by pretest design item.

Fig 1

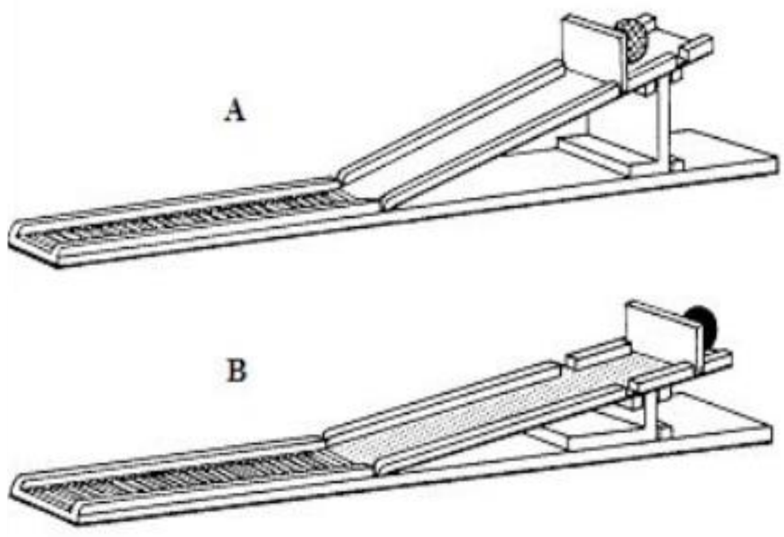
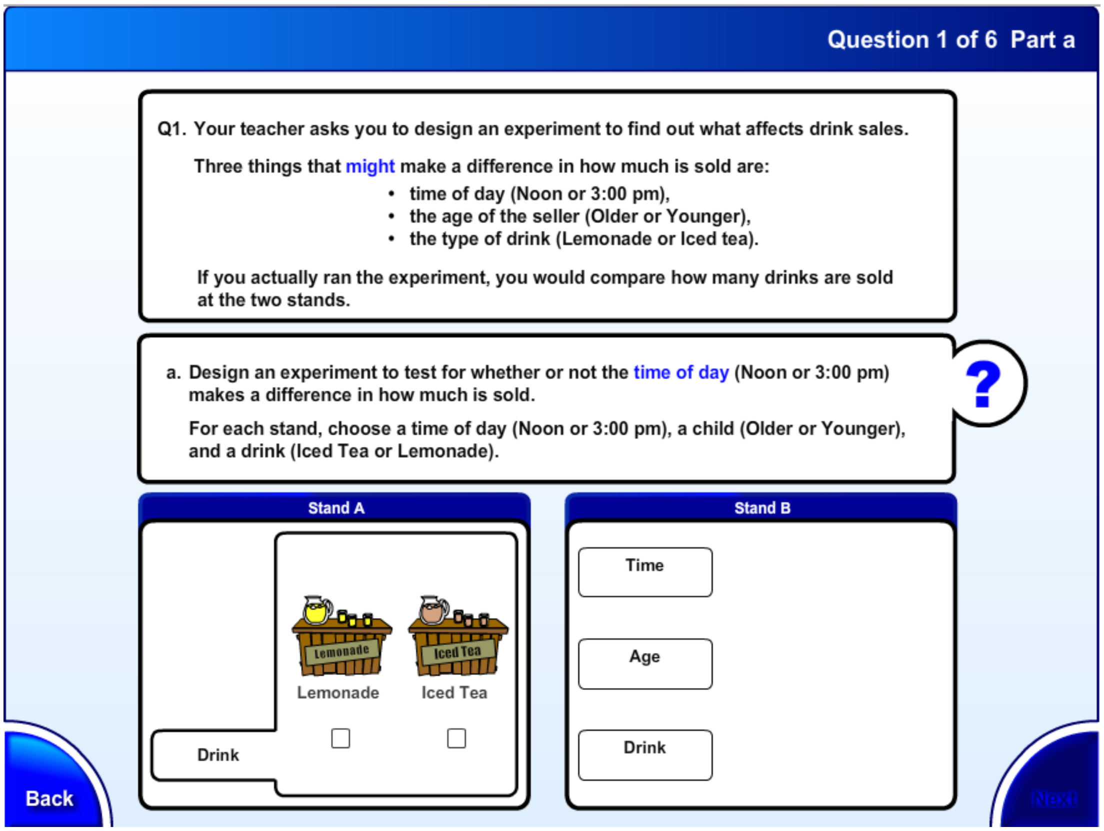


Fig 2



Question 1 of 6 Part a
Q1. Your teacher asks you to design an experiment to find out what affects drink sales.
Three things that might make a difference in how much is sold are:
• time of day (Noon or 3:00 pm),
• the age of the seller (Older or Younger),
• the type of drink (Lemonade or Iced tea).
If you actually ran the experiment, you would compare how many drinks are sold at the two stands.
a. Design an experiment to test for whether or not the time of day (Noon or 3:00 pm) makes a difference in how much is sold.
For each stand, choose a time of day (Noon or 3:00 pm), a child (Older or Younger), and a drink (Iced Tea or Lemonade).
?
Stand A
Lemonade
Iced Tea
Lemonade
Iced Tea
Drink
Stand B
Time
Age
Drink
Back
Next

Fig 3

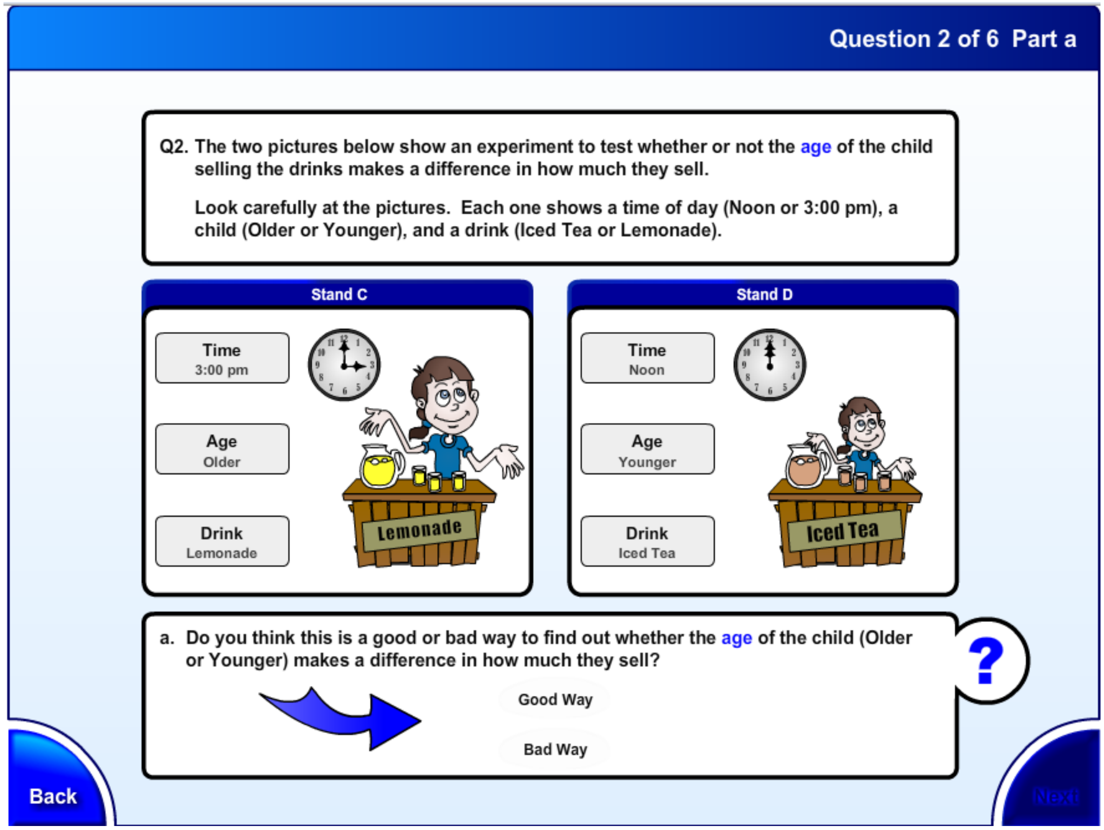

Question 2 of 6 Part a
Q2. The two pictures below show an experiment to test whether or not the age of the child selling the drinks makes a difference in how much they sell.
Look carefully at the pictures. Each one shows a time of day (Noon or 3:00 pm), a child (Older or Younger), and a drink (Iced Tea or Lemonade).
Stand C
Time
3:00 pm
Age
Older
Drink
Lemonade
Lemonade
Stand D
Time
Noon
Age
Younger
Drink
Iced Tea
Iced Tea
a. Do you think this is a good or bad way to find out whether the age of the child (Older or Younger) makes a difference in how much they sell?
Good Way
Bad Way
?
Back
Next

Fig 4

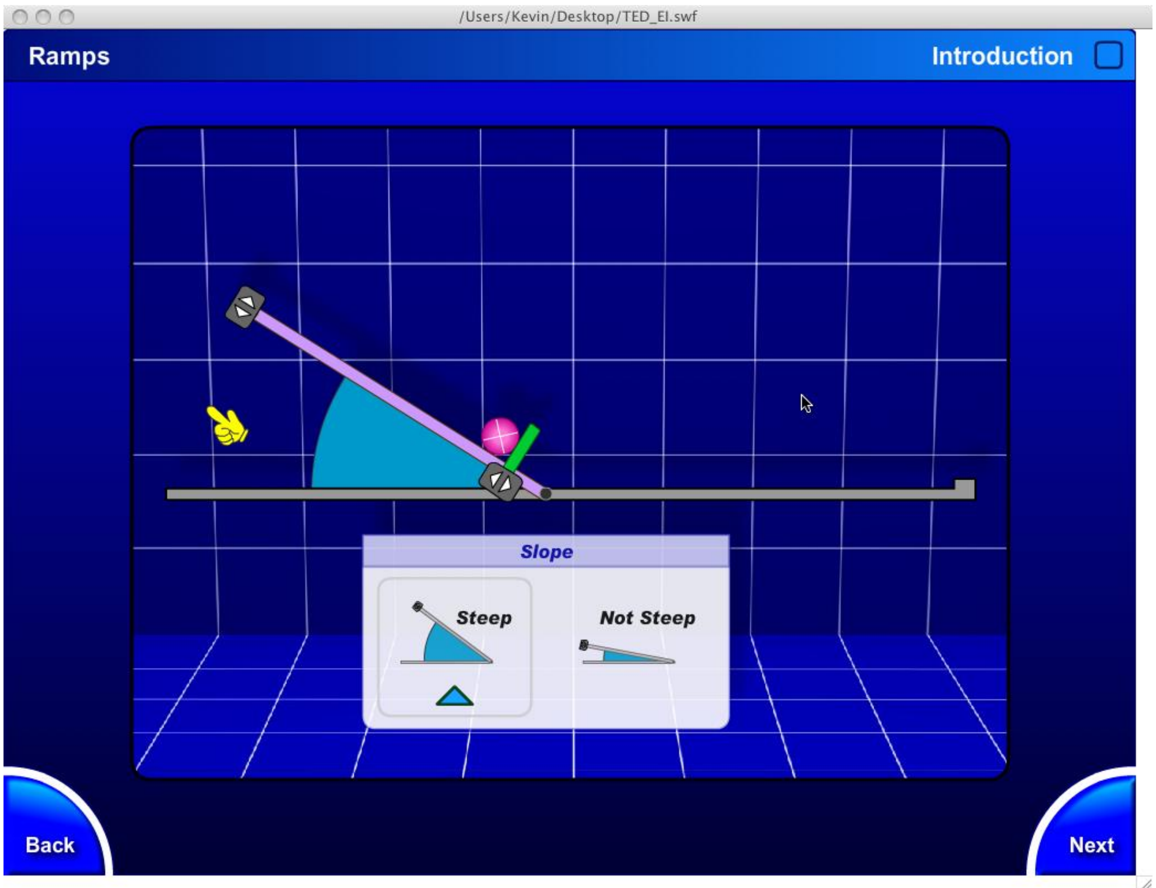

/Users/Kevin/Desktop/TED_EI.swf
Ramps
Introduction
Slope
Steep
Not Steep
Back
Next

Fig 5

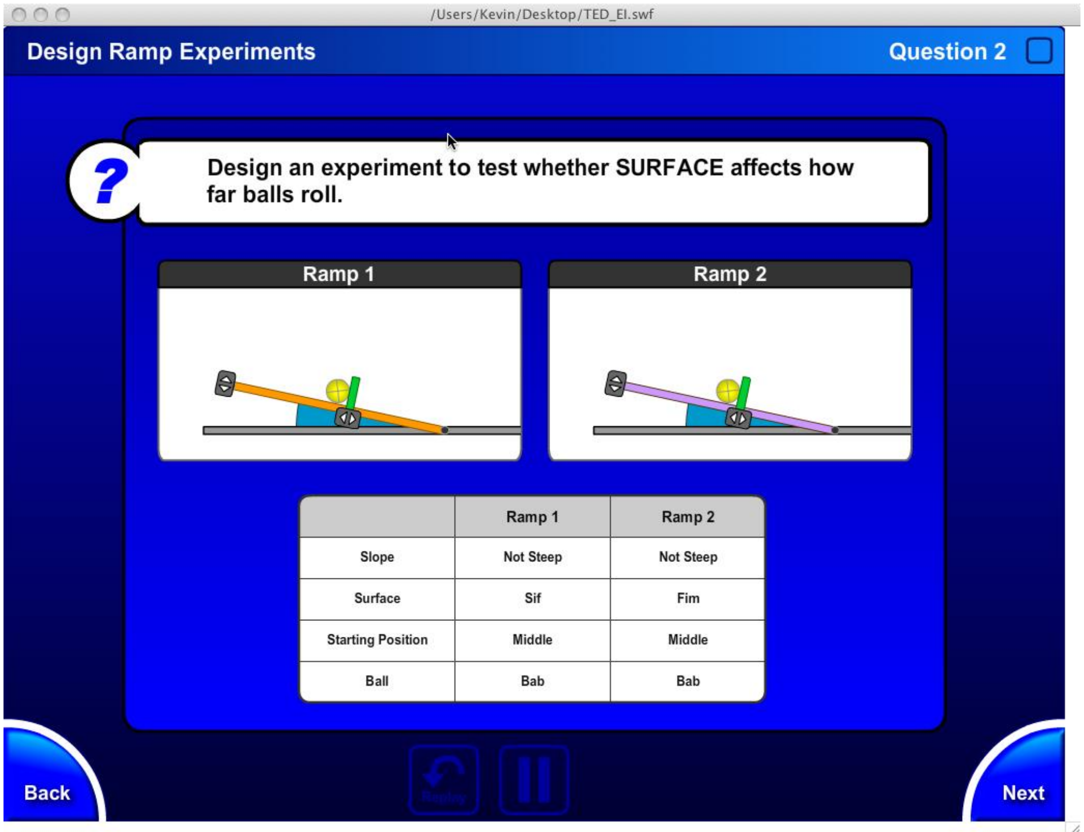

/Users/Kevin/Desktop/TED_EI.swf
Design Ramp Experiments
Question 2
?
Design an experiment to test whether SURFACE affects how far balls roll.
Ramp 1
Ramp 2
	Ramp 1	Ramp 2
Slope	Not Steep	Not Steep
Surface	Sif	Fim
Starting Position	Middle	Middle
Ball	Bab	Bab
Back
Next

Fig 6

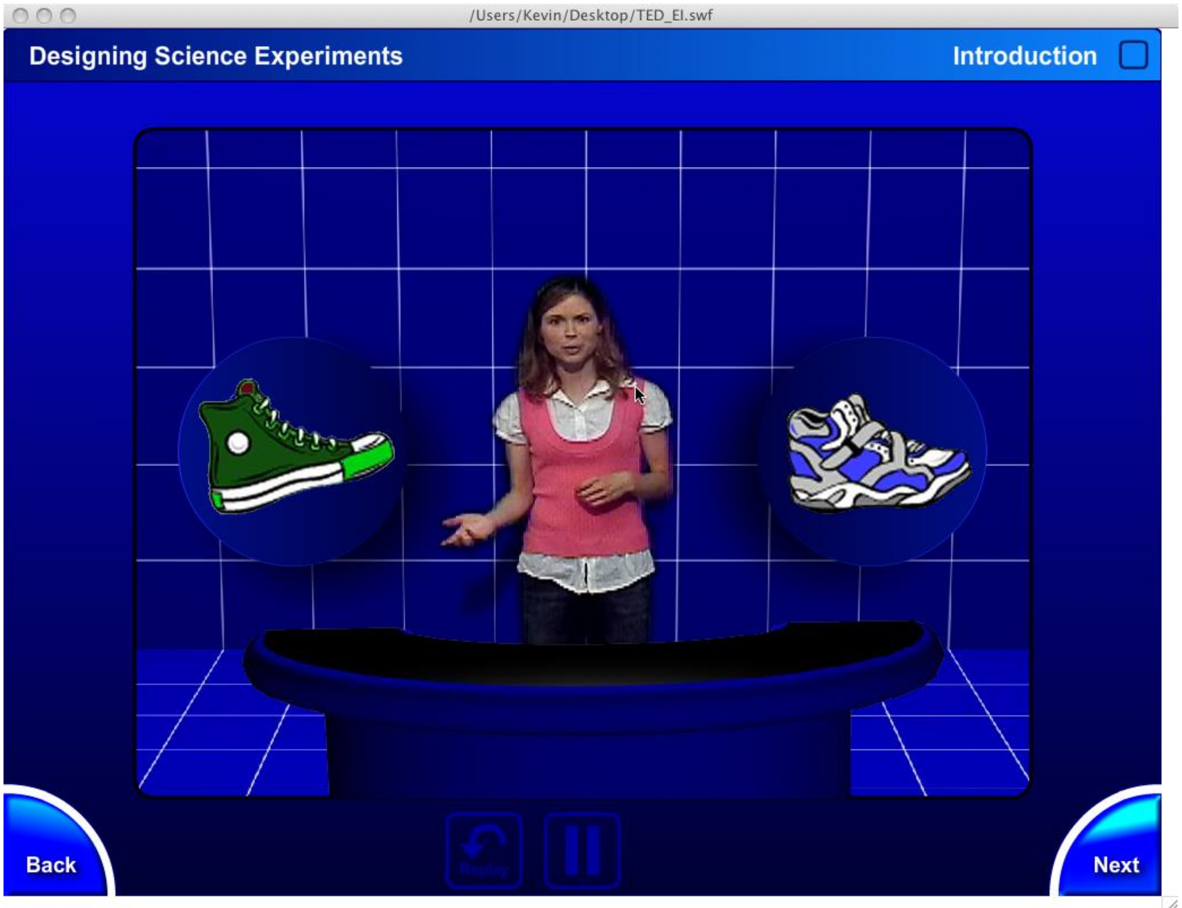

/Users/Kevin/Desktop/TED_EI.swf
Designing Science Experiments
Introduction
Back
Next

Fig 7

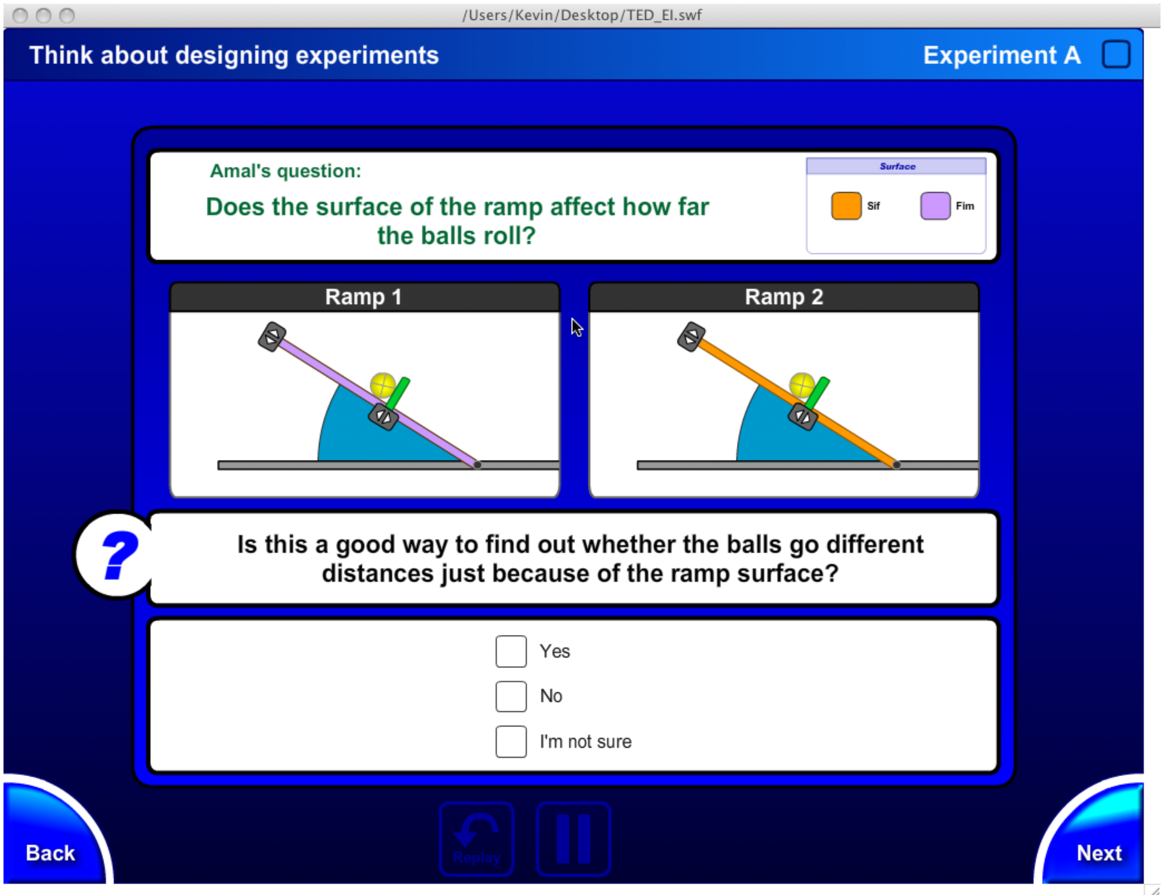
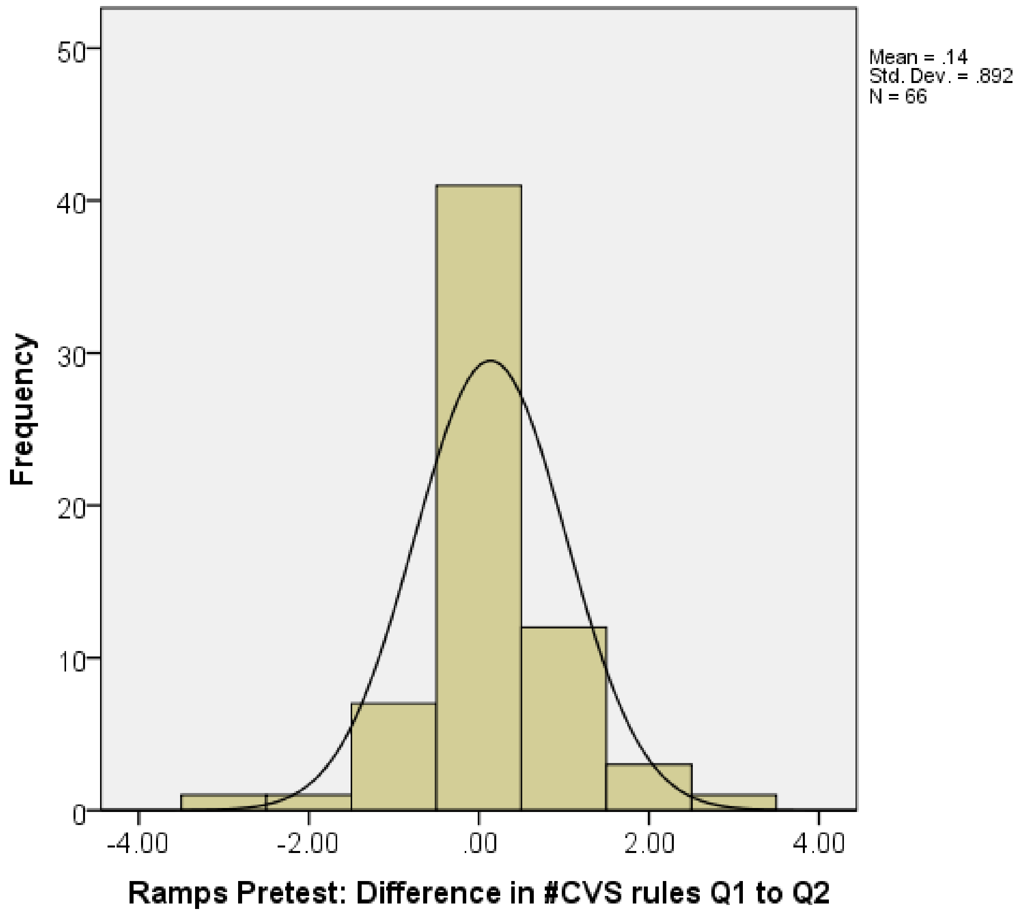
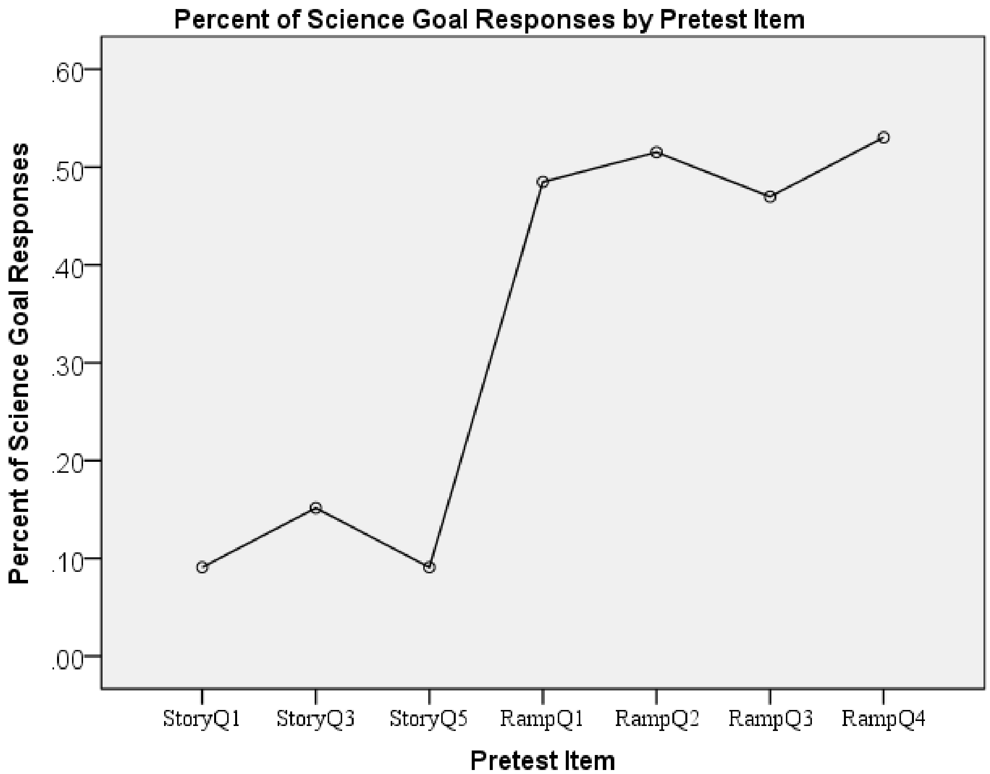

/Users/Kevin/Desktop/TED_EI.swf
Think about designing experiments
Experiment A
Amal's question:
Does the surface of the ramp affect how far the balls roll?
Surface
Sif
Fim
Ramp 1
Ramp 2
Is this a good way to find out whether the balls go different distances just because of the ramp surface?
Yes
No
I'm not sure
Back
Replay
Next

Fig 8



Mean = .14
Std. Dev. = .892
N = 66
Frequency
50
40
30
20
10
0
-4.00
-2.00
.00
2.00
4.00
Ramps Pretest: Difference in #CVS rules Q1 to Q2

Fig 9


Percent of Science Goal Responses by Pretest Item
Percent of Science Goal Responses
.60
.50
.40
.30
.20
.10
.00
StoryQ1
StoryQ3
StoryQ5
RampQ1
RampQ2
RampQ3
RampQ4
Pretest Item