Process and Outcome Benefits for Orienting Students to Analyze and Reflect on Available Data in Productive Failure Activities

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Abstract. Invention activities are Productive Failure activities in which students attempt to invent methods that capture deep properties of given data before being taught expert solutions. The current study evaluates the effect of scaffolding on the invention processes and outcomes, given that students are not expected to succeed in their inquiry and that all students receive subsequent instruction. Two Invention activities related to data analysis concepts were given to 130 undergraduate students in a first-year physics lab course using an interactive learning environment. Students in the Guided Invention condition were given prompts to analyze given data prior to inventing and reflect on their methods after inventing them. These students outperformed Unguided Invention students on delayed measures of transfer, but not on measures of conceptual or procedural knowledge. In addition, Guided Invention students were more likely to invent multiple methods, suggesting that they used better self-regulated learning strategies.

Keywords: Invention activities, productive failure, scaffolding, interactive learning environments, transfer.

1 Introduction

Invention activities are activities in which students generate solutions to novel problems prior to receiving instruction on the same topics. For example, students may be asked to generate methods that capture the variability of given data sets prior to being taught about mean deviation [1-3]. Invention activities facilitate Productive Failure in that students commonly fail to generate valid methods in these activities [4-5]. For example, students may use range or count the number of different values as a measure of variability, ignoring distribution and number of data points. However, the failure is often productive as students learn from the subsequent instruction and practice better than students who receive only instruction and practice, controlling for overall time on task [1,3-6].

Unlike other forms of Productive Failure, in Invention activities students are given carefully designed sets of data, called *contrasting cases*, to invent mathematical methods that capture deep properties of data [7-8]. For example, the contrasting cases in Figure 1 are given to students when asked to create a method for calculating a weighted average. The contrast between Carpenters A and C helps students notice and encode the roles of spread and magnitude. The contrast between A and D helps students notice the role of sample size.

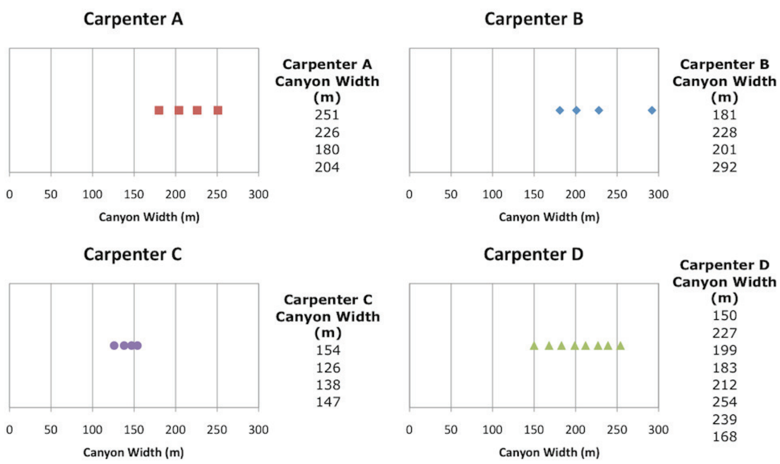

Figure 1 Contrasting cases emphasize the roles of magnitude, distribution, and sample-size in determining weighted average.

The invention process resembles an inquiry process in that students attempt to discover the underlying structure of data [9]. Thus, in the absence of additional support, it is of no surprise that students rarely invent valid methods. However, as described earlier, the invention process improves subsequent learning even in the absence of successful invention [1,2,6]. This raises an interesting question, which we address in this paper: Should the invention process be supported? One hypothesis suggests that supporting invention may lead to improved learning, as students may invent better methods. However, an alternative hypothesis suggests that failure is necessary for learning [10]. Thus, supporting students during their invention process may, in fact, hinder learning.

Scaffolding Invention Activities

One common form of support is scaffolding [11]. Specifically, scaffolding the inquiry process was shown to improve learning in discovery learning [12-13]. Within the context of Invention activities, similar scaffolding was shown to improve the invention process and its outcomes [3]. Within the scope of this study, we chose to focus on scaffolding two key phases that bracket the invention process: orientation and reflection.

Orientation. Invention Activities constrain the inquiry process by offering students contrasting cases to work with. However, simply having the contrasting cases may not be enough. We have previously found that many students working with Invention activities do not engage with the available contrasts when developing their methods [3]. Thus, following a prescriptive cognitive task analysis, we developed and validated prompts that help students orient themselves to the given data. This is done by instructing students to make pairwise comparisons between the contrasting cases with regard to the target concept. For example, students would be asked to compare carpenters A and D in figure 1 to determine which one did a better job of measuring the width of a bridge, see Figure 2. Since the two cases have roughly the same average and spread, students are confronted with the issue of sample size and need to determine whether and how the number of measurements may factor into the problem.

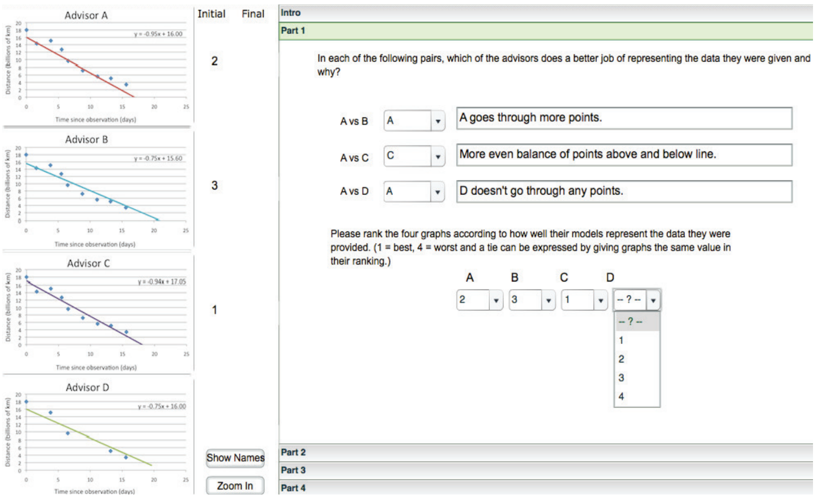

Figure 2. Ranking pairwise contrasts in the orientation scaffold.

Reflecting on the invented method. A second process that we chose to focus on is evaluation and reflection. In addition to being a key process in the scientific toolbox, the process of evaluation is beneficial, as it requires students to self-explain their correct or incorrect reasoning. In the context of Invention activities, once students develop their methods, the scaffolding asks them to explain how their invented methods take into account what they have learned during the pairwise comparisons. Students then apply their invented method to the contrasting cases, and then are asked to evaluate their method by comparing these results to their qualitative rankings as identified by them intuitively in the orientation phase.

Scaffolding students' orientation and reflection processes was found to improve students' invention behaviours and their invented methods on paper [3]. However, we are yet to evaluate the effect of the scaffolding on students' learning gains. The current study evaluates the effect of scaffolding during Invention activities on learning in two ways. First, we evaluate whether scaffolding improves the invention process itself. Given that evaluation and iteration are important inquiry skills, and that multiple invented methods are often associated with better learning in Productive Failure tasks [5], we evaluate the invention process by measuring the likelihood that groups invent more than a single solution. Second, we evaluate the effect of scaffolding on learning outcomes from the overall invention-instruction-practice process. We do so by comparing pre-to-post gains. Notably, these scaffold are static, unlike the view of scaffolding as an adaptive, negotiated process [14]. Understand when students require scaffolding in Productive Failure, and how to detect that using a student model, is outside the scope of the current work.

Method

We compared the Invention activities with and without scaffolding using a pre-to-post design. The *in-vivo* study took place in a first-year physics laboratory course at the University of British Columbia. 130 first-year students from four sections of the course participated in the study. The study was spread across a four-month term with the pre-test and two Invention activities given in three subsequent weeks at the beginning of the term. The final post-test was delivered at the end of the term, roughly two months after students had finished the second invention activity.

Students were randomly assigned to two groups, and different groups were assembled for the two activities. Students in the Unguided Invention (UI) condition worked with a convention invention activity, as defined in [1.2] (n = 65). Students in the Guided invention (GI) condition received the additional scaffolding, as described below (n = 65). Students were given approximately 30 minutes to work on the Invention activities. Each activity was followed by a short lecture on the target domain from the course instructor, which included a group discussion to direct students' attention to the important features of the data. Following the direct instruction, students worked on scientific experiments for roughly two more hours. These experiments provided opportunities for students to practice applying the expert solution from the Invention activities. Topics from the Invention activities were revisited or built on in subsequent weeks.

All students worked on the Invention activities using a dedicated interactive learning environment, the Invention Support Environment (ISE) [15]. Figure 3 shows the interface of ISE for the second activity used in this study, which focuses on evaluating goodness of fit for linear trendlines. The majority of the screen estates are dedicated to an accordion that breaks down the invention process:

- Introduction: background story and task
- Part 1: orientation. I this phase students analyze the contrasting cases qualitatively (available to GI students only).
- Part 2: generation. In this phase students invent a mathematical method to capture the deep property of the data. This is done using an equation editor (shown in Figure 3).
- Part 3: Students were guided to apply their method using a calculator or a spreadsheet software (e.g., MS Excel), and report back their values.
- Part 4: Students were asked to evaluate their methods based on their qualitative ranking (GI condition only).

The left side of the screen presents the contrasting cases to students. These stay available throughout the process. Students can zoom in on the contrasting cases and see the raw data by clicking on the Zoom In button. The centre of the screen shows students their initial and final ranking, when these are available (GI condition only).

The ISE is a skeleton that can deliver a variety of invention activities that share the same structure. It is used regularly by instructors in this course to deliver roughly 5-6 activities per term. A current version of ISE also includes instruction and opportunities for practice within the environment. Authoring new problems in ISE requires designers to give the text and data, but not to author new behaviours, as these are already built into ISE. ISE was built using the Cognitive Tutor Authoring Tools (CTAT) [16].

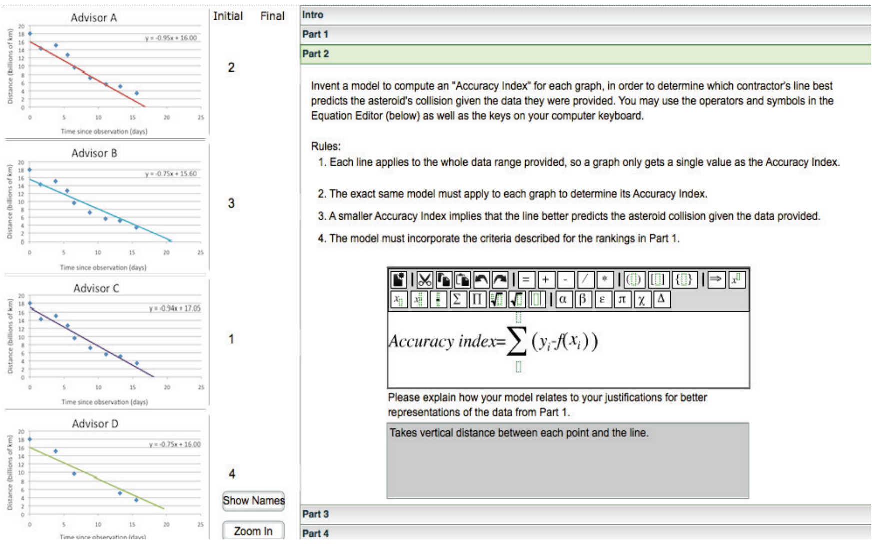

Figure 3: The Invention Support Environment

The two conditions differed with regard to support that students received before and after inventing their methods. The scaffolding that was given to students in the GI condition was modeled after the paper scaffoldings that were used in [3]. These scaffolding were designed to promote expert scientific behaviours that were identified in a prescriptive cognitive task analysis using similar invention activities:

The goal of the Orientation prompts was to get students familiar with the data prior to beginning to invent. Students were asked to compare pairs of contrasting cases and rank these according to the target feature. Students were then asked to briefly explain each of their rankings.

To encourage students to reflect on their invented methods, students were explicitly asked to self-explain their invented methods, referring back to their pairwise rankings. In addition, students were explicitly asked to evaluate their methods by comparing the results of their calculated values with their initial ranking during the orientation.

It should be noted that while the UI group did not have explicit prompts to perform these particular steps, they still had the opportunity to engage in them spontaneously. For example, the implementation process often leads naturally to reflection, as students recognize the shortcomings of their formulas, especially if the students spontaneously analyzed the contrasting cases first. Thus, the main difference between the conditions is the explicit prompting to carry out and reflect on each of the key stages. Table 1 summarizes the differences between conditions. Snapshots of the entire process can be found in Appendix B.

The pre- and post- tests included three types of questions on both invention topics. Procedural items asked students to calculate numeric answers by applying the formulas. Conceptual items asked students to apply the concepts without calculation to demonstrate understanding of the basic principles of the domains. Transfer items provided students with equations that were deliberately varied from the domain formulas and asked students to evaluate whether the formulas were reasonable ways to accomplish the same task. This requires a deep understanding of the deep features of the domain and their mathematical expressions in the equations [17]. Each type of assessment had two items, one on each topic.

Results

There was no effect for condition on pre-test: $t(127) = 0.18$, $p = 0.856$ (see Table 1). A paired t-test found significant learning from pre-test ($M = 0.47$, $SD = 0.24$) to post-test ($M = 0.61$, $SD = 21$) on items that were shared by both tests: $t(129) = 5.75$; $p < .0001$.

Overall, 111 pairs of students worked on the two activities (56 pairs on the first activity and 55 pairs on the second). A logistic regression model found that groups in the GI condition were significantly more likely to create multiple methods, controlling for task, GI = 51% UI = 38%; $B = 1.13$, $SE(B) = 0.56$ $e^B = 3.091$, $Z = 4.02$, $p = 0.045$. The odds ratio (e^B) suggest that the odds to invent multiple methods is three times as high for GI students compared with UI students.

Table 1. Mean (SD) pre- and post-test scores on procedural, conceptual, and transfer items.

Item Type	Unguided Invention	Guided Invention
Pretest:	28% (31%)	33% (32%)
Posttest:		
- Procedural	46% (31%)	47% (28%)
- Conceptual	75% (28%)	74% (32%)
- Transfer	21% (29%)	33% (35%) *

* p < 0.05

An ANCOVA evaluating the effect of scaffolding on learning found no significant effect for condition on procedural, $F(2,127) = 0.02$, $p = 0.882$; or conceptual knowledge, $F(2,127) = 0.09$, $p = 0.761$. However, condition had a significant effect on transfer items, GI: M = 0.33, SD = 0.35; UI: M = 0.21, SD = 0.29: $F(2,127) = 4.81$; $p = 0.030$.

Discussion and Summary

The results presented above show that adding scaffolding to the invention process led to a higher rate of multiple methods during the invention process and to increased gains on a measure of transfer two months after the initial learning period. The scaffold had no effect on procedural and conceptual items. This is not surprising since the invention process itself usually has no benefits for these items compared with direct instruction and practice alone [1,2,17]. Thus, modifying the invention process similarly has no effect on performance on these items.

One key question to be answered is how the scaffolding resulted in the observed improvements. One likely answer suggests a two-fold process. By requiring students to compare pairs of contrasting cases, students notice more features, thus gaining a fuller understanding of the target domain. Using reflection prompts, the scaffolding improves students' meta-knowledge in that it highlights what is known (features) versus what is yet to be learned (the integrated method). Thus, orientation and reflection prompts help students obtain a fuller understanding of the domain, but not necessarily of any specific method. This may explain the observed effect on transfer, but not other, items.

The study further demonstrates that Productive Failure works not simply because support should be delayed. Instead, it is the transmission of domain knowledge that should be withheld, while other forms of support may be beneficial for learning even using the Productive Failure paradigm [6].

The study has several limitations. Most notably, due to the dynamic allocation of students to groups, we did not directly evaluate the relationship between quality of invention and quality of learning. Future work will have to address this issue, as well as focus on topics other than data analysis.

Notably, adding guidance during Invention activities helps learning even though students commonly fail to invent the expert solutions. Thus, not only that the failure to invent is, indeed, productive, but also, some failures are more productive than others. This study demonstrates how engaging students with good scientific practices helps them achieve a more productive failure.

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