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To guide or not to guide: issues in the sequencing of pedagogical structure in computational model-based learning

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This research explores issues related to the sequencing of structure that is provided as pedagogical guidance. A study was conducted that involved grade 10 students in Singapore as they learned concepts about electricity using four NetLogo Investigations of Electricity agent-based models. It was found that the low-to-high structure learning sequences group participants scored significantly higher on the posttest assessments of conceptual and procedural understanding of electricity concepts, whereas the high-to-high structure learning sequences showed no significant changes from pretest to posttest. The implications of these findings are discussed with respect to other research into the sequencing and design of pedagogical structure and guidance in the literature.

Keywords: pedagogical structure; computer model-based learning; instructional guidance; science education; learning designs

The issue of how pedagogical guidance should be provided to learners is a practical one that confronts all educators and at all levels. This issue is also one that has been disputed in the research literature for at least three decades (Mayer, 2004). To understand current theory and research perspectives about pedagogical guidance, Kirschner, Sweller, and Clark (2006) provide a critical review of a number of studies of human learning, which they broadly categorize as (a) direct instructional guidance and (b) minimal instructional guidance. They contrast and compare direct instruction approaches such as research involving worked examples (Miller, Lehman, & Koedinger, 1999; Quilici & Mayer, 1996; Sweller & Cooper, 1985) and process work sheets (Nadolski, Kirschner, & van Merriënboer, 2005), with research involving minimally guided instructional approaches such as constructivism (Jonassen, 1991), experiential learning (Kolb, Boyatzis, & Mainemelis, 2001), discovery learning (Mayer, 2004), problem-based learning (Hmelo-Silver, 2004), and inquiry learning (Van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005).1 In their analysis of the research on learning with these various approaches, Kirschner et al. (2006) conclude
there should be “direct, strong instructional guidance rather than constructivist-based minimal guidance during the instruction of novice to intermediate learners” (p. 84).

We broadly characterize the direct instruction approaches described by Kirschner et al. (2006), as well as other didactic teaching approaches, as pedagogically providing high structure, whereas the minimally guided approaches provide low structure during learning activities. We also observe that in many of the studies they discuss in their review, the main independent variables vary the approach of direct (i.e. high structure) versus minimally guided (i.e. low structure) instruction, with the dependent variables being various assessments of learning or problem-solving success. Such examples can be seen in Albanese and Mitchell’s (1993) review of medical problem based learning (PBL) research and Klahr and Nigam’s (2004) study of direct instruction versus discovery learning for students about experimental design. However, the conclusion of the review by Kirschner et al. (2006) is based only on the studies that primarily control for high structure or low structure. Further, they do not discuss studies that involve different sequences of structure during learning activities, such as Schwartz and Branford (1998), VanLehn, Silar, and Murray (2003), and Bjork and Linn (2006).

Of relevance to this debate on pedagogical guidance is a recently articulated learning design – productive failure (Kapur, 2008, 2011) – that informed the design of the model-based learning activities in this study. Situative and socio-cognitive theoretical perspectives in the learning sciences (Bransford, Brown, Cocking, & Donovan, 2000; Brown, Collins, & Duguid, 1989) and conventional teaching practices tend to initially provide greater amounts of structure when students are learning difficult concepts or engaged in problem-solving activities. This is typically done with the intent of minimizing student failures and frustrations. Indeed, a substantial amount of research has examined the effects of providing various types of structure to learners within ill-structured (IS) problem-solving activities (Puntambekar & Hübscher, 2005). This does not, however, necessarily mean that non-structured or delayed structure learning activities might not also affect important learning gains. Kapur (2008) reported on research into productive failure in which the possibility is explored that there may be conditions in which engaging learners to persist, struggle, and even fail at tasks beyond their current abilities may in fact be an exercise that yields longer term productive learning gains. The productive failure learning design was first tested through a series of classroom-based quasi-experimental studies conducted with approximately 300 11th grade science students across seven Indian schools. Student triads solved either IS or well-structured (WS) problems in an online chat environment. After group problem-solving, all students individually solved WS problems followed by IS problems. Compared to WS problem-solving groups, IS groups initially had difficulties in defining and solving the problems and demonstrated poor group performance in the short term. However, the IS participants subsequently outperformed their counterparts in the WS condition on individual transfer measures, suggesting a delayed or latent productivity in learning resulted from the initial struggle and failure. A second study replicated the research design and findings in three other schools (Kapur & Kinzer, 2009).

Other research has documented how pedagogical trajectories of learning that involve minimally structured activities followed by pedagogical guidance (i.e. delayed structure) might lead to longer term learning gains. For example, research by Schwartz and Bransford (1998) employed the so-called time-for-telling approach. The main results of this study found greater learning associated with an unstructured activity (“time for talking”) followed by a lecture (“time for telling”) that provided more structure subsequently, in contrast to either initially structured or completely non-structured activities. Research by VanLehn et al. (2003) has documented how problem-solving impasses in tutoring sessions (i.e.
low structure) led to enhanced learning from a tutor (i.e. high structure) compared to similar tutor provided feedback in which students had not experienced an impasse in problem-solving. Overall, there is a broad “family resemblance” across the different approaches of Kapur, Schwartz and Bransford, and VanLehn in that each has learners involved with a relatively open-ended or low structure initial activity, which is followed by a more structured activity.

In this paper, we report on a study that explored issues related to sequencing of structure in learning activities. First, we provide a brief overview of the literature related to the sequencing of structure in learning and to learning about electricity with computer models. We then discuss a framework for sequencing pedagogical structures followed by the report on the research findings of this study. Finally, we consider the implications of our findings more generally for the debate on instructional guidance and sequencing of structure in learning activities.

Background

There are two main areas that inform the background to the study reported in the paper. The first is research related to learning scientific knowledge about electricity with computer models, which is the target domain selected for this study, and the second is a framework for the sequencing of pedagogical structure in learning.

Learning the physics of electricity

In discussions with secondary science education teachers in Singapore, where this research was conducted, several teachers mentioned that students find it challenging to learn core ideas about the physics of electricity. We then elected to use the domain of electricity in order to explore research issues discussed above on how sequencing the degree of structure provided during model-based activities might influence learning.

Learning the conceptual dimensions of physics related to electricity has been shown in numerous studies to be challenging as many students have alternative conceptions about electricity that are relatively robust and difficult to change (for a review, see Duit & von Rhöneck, 1997/1998). However, despite the extensive research literature about conceptual difficulties students have with learning about electricity, many classroom teachers primarily rely on algebraic models for teaching this subject (Frederiksen, White, & Gutwill, 1999), and curricula materials about electricity seldom provide a conceptually oriented causal mechanism for explaining circuit principles such as Ohm’s law or how current is propagated within a circuit (Sengupta & Wilensky, 2009). Even when secondary science students are asked to conduct electricity “experiments”, they typically work on WS activities based on scripted worksheets, such as collecting data about effective resistance in series and parallel circuits to verify the algebraic formalism of Ohm’s law.

No doubt contributing to these learning problems, humans are unable to directly perceive the micro-level of how subatomic particles such as electrons behave, so consequently science teachers generally have relied upon instructional approaches that provide macro-level models (e.g. the algebraic Ohm’s law formula) and indications of electrical phenomena (e.g. light bulbs, volt meters). To address this issue, there have been calls to use the representational affordances of computer models to introduce students to visualizations of micro-level models of electricity (i.e. electrons, nuclei, ions) and to then link these models to macro-level models (i.e. current, voltage, resistance) (e.g. Sengupta & Wilensky, 2008, 2009; White, 1993).
While there has been interest in and advocacy for the use of computer models and modeling to help students learn important ideas about a range of physical and social phenomena, this is still a rare learning activity in science classes. Further, as Sengupta and Wilensky (2009) note, there is little agreement about how to pedagogically use agent-based computer models in science classrooms. A central goal of this study was to investigate learning designs involving different sequences for the structure of problem-based activities with agent-based computer models of the physics of electricity.

A framework for sequences of pedagogical structure in learning

As background to our research, we propose a basic framework for sequencing structure for learning and problem-solving activities that consist of (a) high-to-high (HH) structure, (b) high-to-low (HL) structure, (c) low-to-low (LL) structure, and (d) low-to-high structure (LH).4 Of course, the factor of time (i.e. duration) is also important for each sequence component, but for this high-level discussion of a framework for sequencing of learning activities, we assume that the duration of the phases is approximately the same (although this could be an interesting research area to investigate). We further assume that the time of the phases in each category aligns with typical classroom period durations as either fractions or multiples thereof (e.g. two sequences within a 60-minute class and two sequences spread over different class periods), perhaps with some time devoted to formative or summative assessments.

For convenience of discussion, we regard a learning activity that is completely high structure as being in the HH sequence, and completely low structure as being in sequence category LL. Thus, the majority of the direct instruction studies referenced in Kirschner et al. (2006) would be classified as an HH sequence, whereas minimally guided instruction studies would employ an LL sequence. The sequence HL does not seem to be represented in studies cited by Kirschner and colleagues; however, we suggest that approaches such as cognitive apprenticeship (Collins, Brown, & Holum, 1991; Collins, Brown, & Newman, 1989) seem to be aligned with HL in terms of the sequence of expert modeling of the targeted knowledge or skill (high structure) and the fading of scaffolding for the learner (low structure). The sequence LH is exemplified by recent research related to productive failure (Kapur & Bielaczyc, 2012), where there is an initial generation and exploration phase (i.e. low structure) where students express their own representations and solutions followed by a consolidation phase (i.e. high structure) in which the learner comes to organize their representations and ideas into ones that are more aligned with canonical solutions reflecting the practices of a community of practice. Other examples of learning designs for the LH sequence may be found in the work of Schwartz and Bransford (1998), VanLehn et al. (2003), and Bjork and Linn (2006).

Given the interesting findings about the physics problem-solving performance of students in Kapur (2008), we elected to do a study that employed a similar research design, but using agent-based computer models (see below). Briefly, Kapur’s design compared a group of students engaged in an HH sequence (i.e. a sequence of two WS problems) with an LH sequence (i.e. an IS problem followed by a WS problem). Consequently, our experimental design involved two treatment groups that varied in terms of the structure of the model-based learning activities: LH and HH. We hypothesized that the LH sequence of structure for the activities involving the computer models would lead to greater learning about electricity than the HH sequence. We were also interested in the subjective impressions students had about using the agent-based computer models in these two different pedagogical approaches and expected that all students would express interest in using computer models to learn about electricity.
Method
For this study, materials were developed for learning activities involving four NetLogo Investigations of Electricity (NIELS) models. Figure 1 is a screenshot of an electricity NIELS Ohm’s law model (Sengupta & Wilensky, 2007b) that illustrates how current and resistance emerge from simple interactions between electrons and atoms in a wire and battery terminal. Various runs of the model generate output that demonstrates the linear relationship between current \((I)\), resistance \((R)\), and voltage \((V)\), which is symbolically expressed in Ohm’s law (i.e. \(V = I \times R\)). Instead of viewing current and resistance as a macro-level phenomenon as is typical in traditional teaching, here students can observe the micro-level behavior of electrons by varying voltage and resistance at different instances of time. Students also could relate voltage to velocity, current to number of electrons, and resistance to the time taken for electrons to reach from one point to another.

The study ran over four sessions of one hour, each with a different NIELS model: Coulomb’s law (Sengupta & Wilensky, 2007a) during Session 1, followed by Ohm’s law (Sengupta & Wilensky, 2007b), series circuit (Sengupta & Wilensky, 2007d), and parallel circuit (Sengupta & Wilensky, 2007c). In each session, student pairs collaboratively worked on two problems. In the control condition (HH), both problems 1 and 2 were worked on with a structured worksheet, whereas with the experimental condition (LH), the student pairs worked on Problem 1 without a worksheet followed by Problem 2 with the same worksheet as the control condition. After the second problem, the students were given an assessment problem to work on individually. This experimental sequence was used for each of the four sessions of the study (Table 1).

For example, Session 2 consisted of three activities.

- **Problem 1 activity.** For HH group, the structure for this activity was intended to help students learn an important idea relevant to the particular model. The HH group had an activity-based structure with “worksheet-like” questions the students worked on in pairs to answer. The structure provided for the HH condition in the Ohm’s law model used in the second session was in the form of a table to answer a question about the relationship between electron collision rate and current (Table 2). This worksheet structure essentially guided the students as they used the Ohm’s law model to identify the relevant variables, to explore them systematically while making predictions, and thus to increase the likelihood that they would notice the linear relationship between these variables from the dynamic visualization of the electron movements and from the graphical and quantitative outputs that were generated by the model. The LH group was provided with the same question as the HH group, but without this structure.
- **Problem 2 activity.** This problem was the same for both the HH and LH groups, focused on another central idea in the model. The students worked in pairs with the same “worksheet” style structure provided as for the HH group in Problem 1.
- **Daily assessment activity.** The third session activity was an assessment problem that the students in both groups were asked to solve individually. It was intended that a correct solution to the assessment problem for each of the four models would require the students to synthesize and extend the learning from the work on the previous two problems involving the NIELS model-based activities, such as “From activities 1 and 2, can you infer relationship between the voltage and velocity of electrons?” As this activity was an assessment problem, it was not structured for either group.
Data sources

The study was conducted in 2008 in a secondary school in Singapore. Students were randomly paired and each pair was randomly assigned to one of two conditions: 16 pairs in the LH sequence and 16 pairs in the HH sequence, for a total of 64 students. The student pairs worked collaboratively on the first two activities, with the teacher and researchers who monitored the sessions available if there were technical problems or questions about running the software or about understanding the wording of problems. Each of the four model-based units was completed in 60 minutes. Computer screen and webcam audio/video recordings were made of six LH and six HH dyad groups with varying previous academic achievement levels.

Table 1. Session sequences for each NIELS model.

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>Learning activity 1</th>
<th>Learning activity 2</th>
<th>Assessment problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH structure</td>
<td>High structure (dyads)</td>
<td>High structure (dyads)</td>
<td>Low structure assessment (individual)</td>
</tr>
<tr>
<td>LH structure</td>
<td>Low structure (dyads)</td>
<td>High structure (dyads)</td>
<td>Low structure assessment (Individual)</td>
</tr>
</tbody>
</table>

Table 2. Sample of structured worksheet activity for relationship between collision rate and current.

<table>
<thead>
<tr>
<th>Collision rate with nuclei</th>
<th>Time taken to reach battery negative to battery positive</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Student instructions were to use the NIELS model of Ohm’s law to fill in the boxes in order to answer these worksheet questions.
The pretest consisted of 37 multiple choice and factual short answer items and 12 open-ended short answer problems, whereas the posttest consisted of 32 multiple choice and factual short answer items, 12 open-ended short answer problems based on the NIELS model activities, and 7 transfer problems dealing with electricity concepts. On the posttest, four items from the pretest were replaced with parallel items. A physics content expert validated the test items. The multiple choice and short answer items were intended to assess conceptual knowledge, whereas the open-ended problems were designed to assess procedural understanding related to the electricity concepts embodied in the NIELS models. Focus group interviews were carried out with the same 12 students who had the computer screen and audio/video recordings.

Results

Quantitative

Over the four sessions of the study, there were a number of absences that resulted in missing data on the assessments, which reduced the number of students included in the final statistical analysis to 42, with 21 each in the HH and LH groups. There were 10 conceptual areas reflected in the multiple choice and short answer assessment items; however, two of the areas were statistically unreliable, so the final analysis of these items included eight electricity and physics concepts: Coulomb’s force, characteristics of electrostatic force, Bohr’s model, circuit characteristics, conservation of charges, effect of series and parallel connections on bulb brightness, resistive circuits, and open and closed circuits.

Table 3 shows the total weighted scores and standard deviations of LH and HH groups for the conceptual items, procedural items, and transfer problems. For the conceptual items, we assigned a maximum score of 12.5, which made the total maximum score equal to 100 in order to normalize each area. Repeated-measures ANOVA found no significant main effects, even though the HH group had a higher average score on the pretest and the LH scored at a higher level on average on the posttest. There was, however, a significant within-subjects interaction \((F(1, 54) = 10.67, p = .002, \eta^2 = .165)\), which is seen in the decline of the HH group by 4.6 points on the posttest, whereas the LH group gained 12.1 points.

There were 10-paired open-ended questions on the pretest and posttest that were intended to assess procedural understanding about electricity. Reliability analysis of the 10 pretest procedural questions yielded Cronbach’s alpha of .76, so all pretest and the paired posttest procedural questions were summed and normalized on a scale of 100. Repeated-measures ANOVA was run on the summed variables, which showed no significant main effects, with a significant within-subjects interaction \((F(1, 54) = 6.64, \eta^2 = .125)\).

<table>
<thead>
<tr>
<th></th>
<th>LH structure sequence</th>
<th>HH structure sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
<td>Posttest</td>
</tr>
<tr>
<td>Conceptual questions</td>
<td>54.6 (16.6)</td>
<td>66.7 (15.2)</td>
</tr>
<tr>
<td>Procedural questions</td>
<td>42.6 (18.3)</td>
<td>52.1 (13.0)</td>
</tr>
<tr>
<td>Transfer problems</td>
<td>NA</td>
<td>45.3 (22.6)</td>
</tr>
</tbody>
</table>


\[ p = .014, \eta^2 = .142 \] due to the increase of 9.5 points by the LH group compared to the decline of 7.6 points by the HH group on the posttest. Although the LH group scored lower than the HH group on the procedural questions pretest, this was not a significant difference \((p > .08)\). The paired samples \(t\)-tests for the conceptual knowledge measure indicated that the decrease in the HH group’s conceptual test score was not significant \((t(28) = 1.1, p = .56)\), whereas the increase in the LH group’s score was significant \((t(27) = -3.7, p = .002)\). For the procedural measure, paired samples \(t\)-tests indicated that the decrease in the HH group’s procedural test score was not significant \((t(20) = 1.6, p = .126)\), while the increase in the LH group’s score was significant \((t(20) = -2, p = .05)\). On the seven transfer items the Cronbach alpha reliability was a moderate .45. ANOVA tests on a normalized composite transfer score of all seven items as well as on the individual transfer items found no significant differences between the groups.

We also analyzed the performance on the open-ended responses to the three problem activities for each of the four days of the study (Table 4). Two trained raters coded the responses independently and resolved all discrepancies by discussion. The means and standard deviations of the daily problem solutions are shown in Table 4. In conducting the ANOVA tests, Mauchly’s test revealed that the sphericity assumption had been violated for the main effect of activity phase \((X^2(2) = .859, p = .03)\). We adjusted for this by correcting the degrees of freedom using the Greenhouse–Geisser estimates of sphericity \((e = .876)\). There was a significant main effect for the problem scores \((F(1.75, 82.37) = 8.86, p = .001)\), and contrast tests revealed that individual assessment scores in the third activity were lower than in the collaborative second activity \((F(1, 47) = 24.77, p < .001)\). Overall, there was a significant main effect of groups on performance, with the LH group outperforming the HH group \((F(1, 47) = 7.26, p = .01)\), and a significant interaction effect between problem activity phase and groups \((F(1.75, 82.37) = 11.77, p < .001)\). In terms of the comparison across groups for each of the models and problems, there were statistically significant higher solution scores for the LH participants on Model 1 Problem 1, Model 2 Problems 1 and 2, and Model 3 Problem 2 (Table 4).

Table 4. Daily model problem solution scores.

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>LH structure sequence</th>
<th>HH structure sequence</th>
<th>( t )</th>
<th>Sig. (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1 Problem 1</td>
<td></td>
<td>2.41 ( .53 )</td>
<td>1.45 ( .98 )</td>
<td>4.183</td>
<td>.000</td>
</tr>
<tr>
<td>Model 1 Problem 2</td>
<td></td>
<td>2.49 ( .74 )</td>
<td>2.57 ( .65 )</td>
<td>-0.400</td>
<td>.691</td>
</tr>
<tr>
<td>Session 1 Assessment</td>
<td></td>
<td>2.35 ( .57 )</td>
<td>2.35 ( .91 )</td>
<td>-0.010</td>
<td>.992</td>
</tr>
<tr>
<td>Model 2 Problem 1</td>
<td></td>
<td>3.22 ( 1.00 )</td>
<td>1.73 ( 1.66 )</td>
<td>3.732</td>
<td>.001</td>
</tr>
<tr>
<td>Model 2 Problem 2</td>
<td></td>
<td>3.16 ( 0.79 )</td>
<td>2.02 ( 1.46 )</td>
<td>3.274</td>
<td>.002</td>
</tr>
<tr>
<td>Session 2 Assessment</td>
<td></td>
<td>2.58 ( 0.34 )</td>
<td>2.71 ( 0.45 )</td>
<td>-1.080</td>
<td>.286</td>
</tr>
<tr>
<td>Model 3 Problem 1</td>
<td></td>
<td>1.91 ( 0.94 )</td>
<td>2.04 ( 0.97 )</td>
<td>-0.461</td>
<td>.647</td>
</tr>
<tr>
<td>Model 3 Problem 2</td>
<td></td>
<td>1.90 ( 1.02 )</td>
<td>1.11 ( 0.82 )</td>
<td>2.971</td>
<td>.005</td>
</tr>
<tr>
<td>Session 3 Assessment</td>
<td></td>
<td>1.02 ( 0.44 )</td>
<td>.91 ( 0.28 )</td>
<td>1.032</td>
<td>.307</td>
</tr>
<tr>
<td>Model 4 Problem 1</td>
<td></td>
<td>3.46 ( 0.58 )</td>
<td>3.25 ( 0.82 )</td>
<td>1.008</td>
<td>.319</td>
</tr>
<tr>
<td>Model 4 Problem 2</td>
<td></td>
<td>3.12 ( 0.59 )</td>
<td>3.08 ( 0.66 )</td>
<td>0.218</td>
<td>.829</td>
</tr>
<tr>
<td>Session 4 Assessment</td>
<td></td>
<td>2.83 ( 0.80 )</td>
<td>2.88 ( 0.61 )</td>
<td>-0.252</td>
<td>.802</td>
</tr>
</tbody>
</table>

Note: Rows in italics indicate a significant difference between the groups.
As mentioned above, the computer screens and audio/video recordings were made of six dyads in each of the treatment conditions. In order to gain insights into process dynamics of learning in this study, one dyad from each treatment condition was selected for qualitative analysis of the interactions of the participants while working on the learning activities with the Ohm’s law and the parallel circuit NIELS models. Based on teacher ratings and the quality and completeness of the available recordings, we selected a dyad for the LH group that was regarded as academically lower achieving compared to the dyad in the HH group. The audio recordings with time stamps were transcribed to facilitate coding of the screen recordings.

A coding scheme was developed based on the inquiry cycle model of White and Fredericksen (1998) that consists of five components: (a) generation of predictions, (b) design of experiments, (c) execution of experiments, (d) experiment-based inference of relationships, and (e) model-enabled reasoning. The screen capture videos were viewed by two members of the research team who jointly identify events as the student pairs were engaged in each problem-solving activity to create “content logs” (Jordan & Henderson, 1995). The participant pairs also completed paper and pencil work, which was included in the content log events as well.

It was found that the HH dyad group focused on following the instructions in the worksheets for the two learning activities with each of the agent-based computer models and on being careful to get their measurements correct. Their reasoning about the problems, however, was primarily based on their prior knowledge about the mathematical equation of Ohm’s law. The transcripts did not indicate that the participants in the HH dyad used the models to reason the behavior of the electrons in the visualization in the models or about macro–micro relationships associated with the variables of voltage, current, and resistance. The two participants also did not show any awareness of the rate of electron flow in either the single- or two-wire circuits shown in the Ohm’s law and parallel circuit models, respectively.

In contrast, the analysis of the transcripts and screens of the participants in the LH dyad revealed very different interaction patterns. The LH dyad used the first unstructured problem for the Ohm’s law model in a rather unplanned and random manner and they struggled to understand the meaning of some of the representations used in the model. However, when using the model for the second structured problem, the LH dyad was more systematic and observant, such as noting the time it took an electron to travel a certain distance. During the session with the parallel circuit model, the LH dyad did not show any signs of struggle or failure with the first low structure problem. Rather, they used the model in a systematic and purposeful manner as they reasoned about the first problem, which they also did with the second problem. Also, the solutions to the second problems for each of the models by the LH group were longer and more conceptually complete than the HH group.

The interviews provide other insights into the learning dynamics of this study. One participant from the LH group suggested he did indeed experience a sense of “failure” in some of the learning activities:

Because some worksheets was not very specific lah. So we were discussing whether which of variable should be kept constant and which one is, should be changing so that we can answer the question lah. So before we shift the sliders my partner and me will try to hypothesize, like, oh this is directly related to that or in equal-proportion to that, so we try to slide. But in the end all our assumptions were wrong and then we couldn’t find any relations so we keep shifting the
sliders and then we were discussing, ah, why are the results are inconsistent with our assump-
tions and stuff.

It is interesting to note that this participant seems to employ appropriate self-regulated
learning strategies (Azevedo, 2005) such as setting goals (e.g. “try to hypothesize”) and
monitoring the success or – in this case – failure to achieve the goal (e.g. “in the end all
our assumptions were wrong”). Still, in this interview, the student noted that he was confi-
dent he had a much better understanding of electricity and that he was able to write more
detailed problem solutions on the posttest than he did on the pretest. This qualitative meta-
cognitive perception of an enhanced understanding of concepts about the physics of elec-
tricity and the ability to better solve problems in this domain also triangulates with the
quantitative findings of the higher performance of the LH group on the posttest.

It also appears that the HH students were in fact metacognitively aware that they had not
constructed a better understanding of electricity concepts, as reflected in this interview
comment by one of the students in this group:

We, ah, me and my partner asked [the teacher] to clarify some, clarify, some stuff about the
model in question. I prefer that she teach. It will clarify more things … if she teaches.

This comment suggests this student had a metacognitive perception that he needed a
further structured pedagogical activity – the teaching and clarification of “stuff” or concep-
tual perspectives by the teacher – in order to foster the learning. Indeed, the cycle of two
structured problem-solving activities seems to have collectively been an experience of
“failure” for this HH student. In fact, the interviews found that other HH students experi-
enced similar feelings of non-successful learning (whereas none of the LH students men-
tioned this), so the member of our team with a strong physics background worked
through each of the problems with the agent-based models in a structured whole-class pres-
entation session the week after the study ended.

Discussion
The LH group scored lower on the pretest and the HH group scored lower on both the con-
ceptual and procedural questions on the posttest, but neither of these differences was stat-
istically significant. These findings mean (a) the students in the two treatment groups were
statistically at a similar level in terms of their prior knowledge about the targeted knowledge
related to electricity at the start of the study and (b) the HH group had essentially the same
level of knowledge at the end of the study as they did at the beginning.

Before the study, we had two main hypotheses about the learning outcomes: (a) com-
parable learning of conceptual knowledge by both groups and (b) higher performance on
the procedural items by the LH group. The main quantitative findings of this study discon-
firmed the first hypothesis and confirmed the second one. Students in the LH structure
sequence condition better understood the physics of electricity than the students in the
HH structure sequence condition as shown by their significantly higher performance on
the conceptual knowledge items and the more difficult open-ended procedural questions
on the posttest.

No significant differences between the groups were found on within-domain transfer
items on the posttest. We note, though, that the purpose of this study was to investigate
different approaches for the initial learning of knowledge about electricity as part of
model-based problem-solving activities, so the lack of transfer findings was not
unexpected. In fact, the learning activities employed in this study did not directly implement theoretical or empirical guidelines associated with successful transfer identified in other research (Bransford & Schwartz, 1999; Gentner, Loewenstein, & Thompson, 2003; Jacobson & Archodidou, 2000).

The sets of problem solutions for each of the models used in the four sessions of the study and the qualitative analysis of the dyads for the second and third models help provide insights into the learning dynamics of this intervention. In particular, these findings seem consistent with the framework of a generation and exploration phase (low structure) and consolidation phase (high structure) as proposed by Kapur and Bielaczyc (2012). For the daily problem activities, there was an unexpected higher score on Model 1 Problem 1 for the LH dyad, even though this was an unstructured problem for them and a structured problem for the HH dyad.

Of theoretical interest for the sequencing of pedagogical structure, however, were the significantly higher scores for the LH dyad on the second session with Model 2 Problems 1 and 2. Consistent with the processes associated with productive failure learning designs (Choi, Yogi, Shepardson, & Charusombat, 2010; Kapur, 2011), we believe the Model 1 problem-solving activities served as the generation phase for the LH students wherein they activated a range of prior “pieces of knowledge” or “p-prims” (diSessa, 1993) as they interacted with the computer model, which is also suggested in the qualitative analysis of the LH dyad. During the activities for Model 2 Problems 1 and 2, the LH students consolidated their understandings of the behavior of the electrons in the Ohm’s law model and consequently scored higher on those two problem solutions. The transcripts do suggest the LH group was somewhat random in how they used the Ohm’s law model in Problem 1. However, during the structured Problem 2, they were more systematic in using the model as well as noticing things not directly required in the worksheet script, such as noting the time electrons took to travel a set distance. These findings suggest that the interaction with the agent-based models in an unstructured matter facilitated the students’ initial exploration of properties of electron’s behaviors and their later deeper understanding of Ohm’s law. In particular, the LH dyad students were starting to experience a consolidation of their understandings by systematically using the representational aspects of the model and constructing conceptual links to the mathematical formalism of Ohm’s law.

This is also evidenced by the interviews with the LH participants, such as the one quoted above. These interviews suggest that there was a sense of “failure” at times in the earlier learning activities when their assumptions were conflicting with what they saw in the model, but that by the end of the study, there was a reasonably solid understanding of this content – that is, a “productive” overall learning experience. The interviews with the HH sequence participants, however, suggested there was little overall sense of productive learning, which was consistent with the low quantitative performance on the posttest.

Recall the discussion of the framework for the sequencing of structure in learning activities we proposed earlier: (a) HH structure, (b) HL structure, (c) LL structure, and (d) LH structure. The main results of our study indicate that an LH structure sequence yields superior learning compared to an HH structure sequence. This study did not have a condition for HL, and so future research could directly explore the efficacy of LH compared to HL sequences. As mentioned earlier, we believe there is a convincing amount of research that demonstrates LL sequences (e.g. “pure” discovery learning) are rarely effective for learning new knowledge and skills (Mayer, 2004), and so we do not recommend future research in that component of the sequencing framework.
The question may be asked if the differences in performance of students were due to the sequencing of activities rather than other factors present in the learning environment, such as (a) self-regulation, (b) familiarity with computer simulations and/or agent-based computer models, or (c) the presence of alternative conceptions before the study. We controlled for these factors through the use of random assignment to the two treatment conditions. Further, related to the third factor of alternative conceptions, we found no evidence on the pretest items of systematic differences in prior knowledge about electricity. Given we can rule out major alternative explanations for differences between the treatment groups such as these, then the results of this study stand to confirm the hypothesis that the higher performance of the experimental condition was due to the learning efficacy of the LH structure sequence of the learning activities.

Recall that the main claim of Kirschner et al. (2006) discussed above is that direct instruction (i.e. HH in the framework) is instructionally more powerful than minimally guided instruction (i.e. LL in the framework). The results of this study seem to challenge this claim. One explanation for this discrepancy is to observe, as we mentioned earlier, that the research selected for inclusion in the Kirschner et al. paper did not include studies of LH or HL sequences of structure; that is, they selected to discuss research that did not control for sequencing of pedagogical structure. Thus, the results of this study are not necessarily inconsistent with Kirschner et al. if their review is interpreted as HH versus LL. Rather, this study and other research such as productive failure (Kapur, 2008, 2011; Kapur & Bielaczyc, 2012) provide an extension to the Kirschner et al. (2006) perspective by adding an LH condition.

Interestingly, one of the main studies cited by Kirschner et al. in support of the superiority of direct instruction is Klahr and Nigam (2004). This research explored helping third and fourth grade students to learn about experimental design with two different instructional conditions: direct instruction and discovery learning. They reported that participants in the direct instruction condition scored higher on the posttest than the discovery learning condition, hence their conclusion of the superiority of direct instruction. This is a finding Kirschner et al. (2006) highlighted in their paper to support their similar view. However, the actual experimental design employed by Klahr and Nigam included a pretest, which asked the students to setup four small experiments, after which the students were assigned to either the direct instruction or the discovery learning training condition. The pretest was in fact a low structure activity that the majority of the students performed at a low level (i.e. they failed), followed by the direct instruction and discovery learning treatments, and then the posttest assessments. Thus, this study actually demonstrates the efficacy of LH versus LL sequences of structure effects and is not a study that involved pure direct instruction or sequences of high structure. Consequently, we suggest future research could more fully explore different design approaches for the sequencing of pedagogical and problem-solving structure, especially for LH types of sequences – such as productive failure, desirable difficulties (Bjork & Linn, 2006), impasse driven learning (VanLehn et al., 2003) – and that these be compared with other learning designs for HH (e.g. direct instruction) and HL (e.g. cognitive apprenticeship; Collins et al., 1989).

The findings and arguments presented in this paper suggest future research might explore learning designs in which students engage in an initial low structure learning activity where they will likely struggle, make mistakes, or fail followed by a structured activity such as the use of worksheets as in our study or perhaps different approaches to direct instruction such as Kirschner et al. (2006) recommend. In particular, we suggest three research areas future studies might explore.
First, for the initial low structure activity, is there a “zone of proximal failure” (ZPF) for the types of problems or activities? Problems outside of the ZPF might be too easy – meaning the students already understand that knowledge – or be too difficult – and thus students might not persist in the low structure activity and thus not setup the cognitive learning conditions (i.e. elicitation of ideas) for conceptual consolidation in the subsequent high structure activity. Second, what might be the appropriate durations for the initial low structure activity? Might there be “productive” low structure activities that are relatively short – perhaps 1–15 minutes? Might a low structure activity have a longer duration, such as an entire class period or multiple class periods? What might be optimal durations for the high structure activities? Third, might age, academic achievement levels, or subject areas (e.g. mathematics, physics, chemistry, biology, history, sociology, humanities, language learning) be factors that interact with issues explored in research areas #1 and #2? Certainly, there are many other research areas to investigate, but work in these three areas we believe would build on research reported in this paper and other papers we have referenced.

Conclusion

This study may be situated in the long running debate about the degree of pedagogical guidance that learners should receive (Kirschner et al., 2006). After discussing conflicting perspectives in this literature, we propose a general framework for the sequencing of structure in learning activities from which to look at issues associated with providing pedagogical guidance. An implication of the findings in this study is that there are learning trajectories and activities – in this case, ones in which initially unstructured problem-solving tasks were followed by more structured ones – that could lead to significantly enhanced learning outcomes. These results are also consistent with research that has demonstrated how computer-based models may be used to help students learn scientific knowledge and skills (e.g. Sen-gupta & Wilensky, 2008, 2009; White, 1993). However, in our research, the interactive and representational affordances of the computer-based models alone were not sufficient to affect learning gains of difficult scientific knowledge. Rather, the affordances of the agent-based computer models and visualizations used in this study in conjunction with a set of LH structure learning activities were found to help students construct understandings of physics concepts about electricity compared to students using the same models and solving the same problems using a HH structure sequence. We hope this research contributes to further insights into the characteristics of learning trajectories with computational model-based learning and non-technology enhanced classroom environments, with perhaps the counterintuitive perspective that students may not need initial structure to prepare them for learning, but rather, they may better benefit from doing and trying first in low structure experiences in order to then benefit from subsequent high structure pedagogical guidance.

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Notes
1. The references for these various instructional approaches listed in this sentence are drawn from Kirschner et al. (2006).
2. “Structure” may be broadly conceived in a variety of forms such as structuring a problem, scaffolding, instructional facilitation, providing worksheets or scripts, and so on.
3. We revisit Klahr and Nigam in the discussion of our findings and challenge their interpretation of their results.
4. This section elaborates on earlier considerations of the sequencing of pedagogical structure by the first and second authors (Jacobson, Kim, Miao, Shen, & Chavez, 2010).
5. The posttest had five fewer multiple choice and short answer items than the pretest. This was done to slightly shorten that section of the posttest given there were new transfer items for the students to answer.
6. For effect sizes, a partial $\eta^2 = .01$ is considered small, .06 medium, and .14 large.
7. For a complete discussion of the qualitative analyses, see Pathak, Kim, Jacobson, and Zhang (2011).
8. The use of “lah” is a Singaporean colloquial expression that comes at the end of a sentence to provide an emphasis.

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