Dynamic Visualization of Motion for Student-Generated Graphs

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Abstract: Graph construction and interpretation are critical 21st-century skills. In this study we investigate how 8th grade students construct graphs in the context of a week-long online curriculum unit that links dynamic visualizations to graphical data. We test two forms of visualization: dual animation depicting both the student's graph and the correct graph in terms of a narrative context and single animation depicting only the student's graph. Quantitative results indicate that both forms of animation supported understanding, but dual animation facilitated construction of more accurate graphs earlier in the unit. Case studies reveal unique graphing patterns associated with each form of animation.

Introduction

In this research we compare two forms of graph visualization to explore how new technologies can improve graph understanding. Graphing is a critical mathematical and scientific skill, as well as a key practice used in personal and policy decisions. Growth in the field of data science suggests that the ability to apply graphing knowledge in a broad range of contexts will be an increasingly valuable 21st-century skill. As such, new standards assert that students translate between quantitative, graphical and narrative forms (NGACBP, 2010). Given documented student difficulties with graph understanding (Shah & Hoeffner, 2002), we seek tools that can help students interpret graphs. We test a graph visualization tool under two conditions to explore how feedback on graph construction can improve graph understanding.

Graph understanding involves a variety of thinking skills, ranging from basic perceptual processing to highly complex cognitive reasoning (Shah & Hoeffner, 2002). Successful graph construction and interpretation requires students to coordinate between multiple representations (e.g. text, tables, and graphs in various formats) and sources of knowledge (e.g. perceptual, contextual, and mathematical). Given the complexity, iterative refinement of instruction and testing of comprehensive alternatives is valuable (Quintana et al., 2004).

To promote graph understanding we designed instruction using the Web-based Inquiry Science Environment and the knowledge integration (KI) framework and tested alternative uses of our visualization tools (Linn & Eylon, 2011). The KI framework has proven useful for design of instruction featuring dynamic visualizations (Ryoo & Linn, 2012). The pattern guides students to articulate predictions, add new ideas, distinguish between predictions and new ideas, and reflect on the problem. When students articulate their ideas, including non-normative ideas, they are prepared to compare and contrast these ideas with alternatives introduced in the curriculum. By facilitating reflection on contrasting ideas, technology can support robust conceptual change.

While the general pattern of the KI framework is widely applicable, the specific activities associated with each aspect of the KI pattern are dependent on the conceptual domain and available technologies. For graphing, we can elicit ideas by asking students to interpret a graph or to construct a graph about a complex situation. Research shows that students often generate a "pictorial" interpretation of the graph rather than capturing a relationship (Leinhardt, Zaslavsky, & Stein, 1990). For position vs. time plots (position-time), students often make a pictorial interpretation when they report that a flat line segment represents an object moving forward along a straight path, or that a non-zero slope represents an object moving up or down (Mokros & Tinker, 1987). Additionally, students may generate a graphical representation of an object "moving back" to a reference point by drawing a line that essentially goes back in time. This response does not recognize that a position-time graph will always move forward in time (i.e., from left to right).

Dynamic visualizations (e.g. animations) have successfully promoted acquisition of ideas about graphs (Moreno, 2001) and specifically about motion graphs (Imhof, Scheiter, Edelmann, & Gerjets, 2013). For example, in the SimCalc software MathWorlds (Roschelle, Kaput, & Stroup, 2000), students view the animation of an elevator that moves according to the shape of a segmented line graph. Likewise, Ploetzner, Lippitsch, Galmbacher, Heuer, and Scherrer (2009) depict line graphs through an animation of a runner. By observing these linked representations students have the opportunity to discover relationships between abstract spatial features (e.g. slope) and narrative events.

Our research extends this line of investigation to activities that help students distinguish among ideas about motion graphs. Distinguishing requires that students develop and apply criteria to evaluate ideas and then compare multiple ideas based on these criteria. This multi-step process represents a significant design challenge, given inherent limitations on students' working memory (Sweller, 1988) and ability to attend to multiple visual phenomena within the same sensory modality (Mayer, 2001). A general solution is to reduce cognitive load by distributing information to the environment so that the learner has less information to maintain in working memory (Zhang & Norman, 1994).

For narrative-based position-time graphs, ideas may be elicited by prompting students to graph the narrative. Animated feedback depicting the motion inherent in these graphs ("student animation") then provides an opportunity to evaluate ideas by comparing observed motion to the imagined motion of narrative events. While this may be straightforward for simple narratives, for complex narratives the burden of remembering the sequence of events may overwhelm students. Furthermore, for subtle changes in motion the student may not clearly recognize any incongruity with the narrative text, as he or she interpreted it. In this case the mental reference by which the animation is evaluated is challenging to construct and difficult to maintain in memory.

A potential remedy is to provide an additional concrete reference animation that accurately depicts the narrative ("normative animation"). While this design would seem to reduce the burden on students, there may be unintended consequences of introducing a new visual representation. For example, splitting attention between the two animations may inhibit comprehension (Mayer, 2001). Additionally, by relying solely on the normative animation, rather than generating a mental simulation of the narrative, students may miss an important learning opportunity (Black, Segal, Vitale, & Fadjo, 2012; Vitale, Black, & Swart, 2013). Furthermore, reliance on visual feedback has been associated with application of opportunistic trial-and-error strategies, which can interfere with learning in a digital environment (e.g., Logo, Cope & Simmons, 1994).

In this research we compare the use of dual animations (Student+Normative condition) to a single animation (Student-only condition). We hypothesize that the Student+Normative condition will facilitate the production of more accurate graphs but anticipate that each condition has some advantages. We take an exploratory approach to analysis of student strategies, and how they reflect affordances of the graphing tools. We take an in-depth look at individual students' graphing artifacts to evaluate how emergent strategies may promote or inhibit learning.

Methods

Participants and Procedures

Three teachers from two suburban middle schools chose to participate in this study. A total of 384 eighth grade students participated in some part of this study. Out of these students 333 students completed the pretest, (some part of) the curriculum unit, and the posttest. The populations served by school these schools differed markedly in income-levels and home language [School A: N = 319, 7% reduced lunch, 3% ELL; School B: N = 65, 63% reduced lunch, 25% ELL]. Both pretest and posttest were administered to children individually. Pairs of students were assigned to collaborative workgroups by their teacher to work on curriculum. In one class within School B students worked individually. Workgroups were randomly assigned to a condition [S+N or S-only] by the software and received one of two sets of similar activities. While graphing, students seeking help were directed by either the classroom teacher or researcher to complete the graph and observe the animated feedback.

Curricular Materials

This study was conducted in the context of a curriculum module entitled *Graphing Stories*. The goal of the unit was to familiarize students with the process of constructing graphs and interpreting graphs in terms of narratives. The curriculum was developed within WISE (Web-based Inquiry Science Environment), utilizing a variety of instructional and assessment tools (Linn & Eylon, 2011). Within a WISE module each page displayed on screen is referred to as a "step". Groups of related steps are referred to as "activities".

Table 1: Curriculum layout for "Graphing Stories"

#	Activity Title	Description/Goals	Relevant Steps
1.	*Graphs Tell a Story*	Intro to graphing concepts.	
2.	*Retell the Story with Graphs*	First narrative graphing exercise with animated feedback.	2.2/2.3/2.4 – Table/Graph "Bear Story"/Feedback (*Bear* item)
3.	*Graphing Movement*	Direct instruction on the relationship of slope to speed and direction.	3.3/3.4 – Graph person standing still/Feedback 3.7/3/8 – Graph person moving forward and back/Feedback 3.11/3.12 – Graph person moving fast and slow/Feedback
4.	*Trading Graph Instruction*	Peer review of narratives based on graphs.	
5.	*Drive Your Car*	Second narrative graphing exercise, with student control of axes to adjust scale.	5.2/5.3/5.4 – Table/Graph "Sam's Journey"/Feedback (*Sam* item) 5.6 – Graph "Rita's Journey"
6.	*Your Story*	Personal narrative and graphing exercise.	

Table 1 displays the general layout and features of the *Graphing Stories* curriculum unit. In the context of this study we highlight the steps that feature table and graph construction, followed by an animated feedback. Figure 1 display the feedback layout for the "Bear story" and "Sam's journey," respectively.

Figure 1. Screenshot of animated feedback tool (Student+Normative), *Bear* item (left) and *Sam* item (right).

For feedback on the *Bear* item, displayed in Figure 1 (left), the lower half of the image displays a student-constructed graph imported from the previous step. Above the graph, animated "hikers" move adjacent to a number line representing the range of the narrative. The lower "hikers", marked with a red star, move according to the normative solution, while the upper "hikers" move according to the student graph. The vertical red line in the graph indicates the current time in the animation and moves from left-to-right. At the current state in the animation (40 minutes), the story indicates that the hikers should be resting at the "lunch spot"; however, this student did not include a resting segment, resulting in a visual discrepancy. For the *Sam* item (Figure 1, right), the animation depicts the motion of cars. In this case the graph incorrectly represents "going back" as a reversal in time, thereby producing a non-functional graph. In all versions of the animation, during those periods of time when the hikers or car is predicted to be at multiple positions at once, the student-based image of the hikers or car is replaced by the word "ERROR" to indicate that the graph cannot be animated appropriately.

Test Materials

The pretest and posttest included graph interpretation items in mixed multiple choice and open response formats. For this study we focus on two open response items. In "The Race", students were asked to interpret an incomplete graph representing two runners racing towards a finish line from different starting positions (Figure 2). Students were asked to predict the winner and provide a scientific explanation for their choice. For "A Journey" students were asked to select and explain which of three graphs of distance over time – including two non-functional graphs – could represent a bicycle ride. Both items were intended to elicit students' non-normative concepts about slope and speed. Items were coded independently by two researchers, differences were resolved by consensus (inter-rater agreement: *Race:* kappa = .88; *Journey*; kappa = .80).

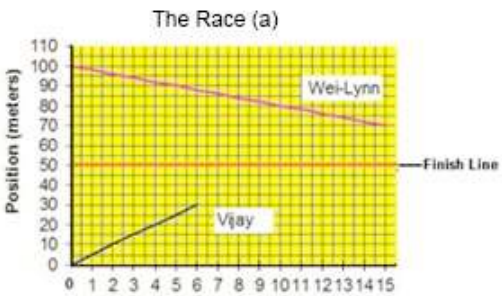

Figure 2. Graph for "The Race" item given in pretest and posttest.

Analysis Approach

All graphs generated by students for the *Bear* and *Sam* items in *Graphing Stories* were scored using an automated algorithm according to the rubric displayed in Table 2. First, student graphs were evaluated for the presence of up to four specific features corresponding to concepts addressed in the unit, including: where to place the initial point and how to represent "moving back", "not moving", and a change in speed. The presence of a feature was assessed either, in the case of a single point, by evaluating whether the point deviated from the expected coordinates less than a threshold or, in the case of a slope, by evaluating whether the rise and run of the segment deviated from expected less than a threshold (in both cases approximately 5% of axis length). Second, a score was constructed to reflect the number of detected features.

Table 2: Graph scoring rubric: features and scores

Feature	**Description**
Initial Point	Initial point (time = 0) is placed at expected coordinates
Backwards (neg. slope)	"Moving backwards" is represented with a negative slope segment
Motionless (zero slope)	"Standing still" is represented with a zero slope segment
Speed change	"Slow" to "fast" is represented with two segments with differing slopes
Score	**Description**
3 - 6	Total # of features present in graph (at least once) + 2
2	If no features detected, were there at least two points?
1	Less than 2 points were detected

For both *Race* and *Journey* items a KI rubric was applied to assess the extent to which student response supported multiple normative ideas, linked in a coherent manner (Linn & Eylon, 2011). In the case of graph items normative ideas may include numerical evidence, relevant spatial characteristics of the graph (e.g. slope), formal concepts about graphs (e.g. functionality), and relevant connections to the narrative context (Table 3).

Table 3: KI scoring rubric for "The Race" pre/post open response item.

Score	**Level**	**Description**	**Examples**
0	**No Answer**		
1	**Offtask**	Does not address question	*I don't know.*
2	**Irrelevant/Incorrect**	Wei-Lynn is faster than Vijay or other incorrect statements	*I think Wei-Lynn will win the race because she is already ahead of Vijay.*
3	**Partial** Normative isolated ideas without a valid link	General observations of the graph OR statements about speed with no reference to the graph	*Vijay is running faster, he will win*
4	**Basic** Elaborate a scientifically valid link	Connects observations from graph to speed or compares lines based on distance or time	*I predict Vijay to win the race because he was closer to the finish line 6 seconds after the race began, meaning he has a higher rate of speed.*
5	**Complex** Elaborate two or more scientifically valid links	Connects observations from graph to Vijay's speed AND Connects velocity or slope to distance and time	*Vijay is traveling faster, because his line has a greater slope. His speed is 5m/s, while Wei-Lynn's speed is 2 m/s. Though Wei-Lynn's line seems longer, Vijay will reach the finish line faster.*

Results

An ANOVA of the pooled pre- and posttest data revealed a significant effect of testing session [$F(1, 331) = 18.6$, $p < .001$], demonstrating that across both conditions students made gains from pre- to posttest (Figure 3). However, neither a main effect of experimental condition [$F(1, 331) = 0.3$, $p > .1$], nor an interaction between condition and testing session emerged [$F(1, 331) = 1.4$, $p > .1$].

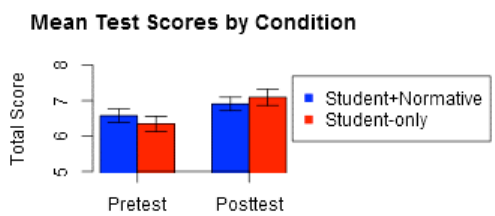

Figure 3. Mean scores for pretest and posttest, by condition

These results suggest that both conditions were equally effective in terms of promoting student graph understanding. This could either indicate that the addition of the normative animation did not affect students' graph construction strategies, or that the emergent strategies had similar effects on student learning, on average. To address this distinction we investigated initial and final graphs for *Bear* and *Sam* graphing items (Figure 4).

For the *Bear* item, while students in both conditions began with similar scores for their initial graphs, students in the S+N condition completed the step with more accurate graphs than students in the S-only condition [t(202) = 2.6, p < .05]. In contrast, while the final graphs of the *Sam* item did not differ by condition, students in the S+N condition produced more accurate graphs initially [t(141) = 4.5, p < .001].

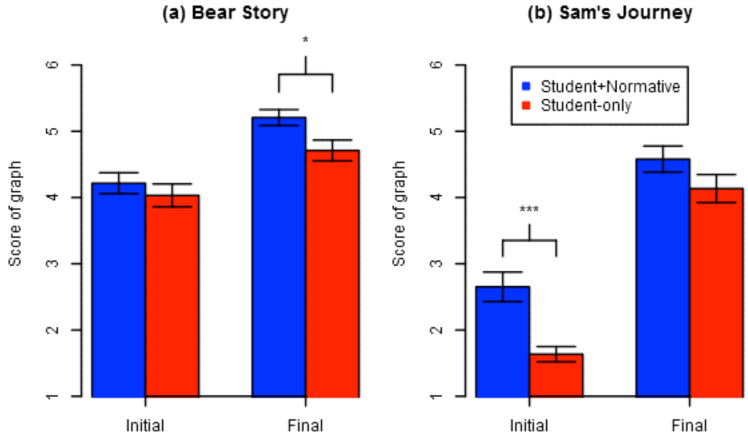

Figure 4. Comparison of initial and final graph scores for two curriculum items, by condition. (Note: for all figures and tables p-values denoted as such: *** p < .001, ** p < .01, * p < .05, † p < .1)

Across both conditions, for both items, there was a clear improvement from initial to final graphs; however, this could have been due to students taking an iterative strategy of deliberately plotting partial graphs (which would not attain high scores, initially). To determine whether the feedback tool promoted more accurate revisions, rather than simply more complete revisions, we compared the accuracy of the first graph produced with at least 4 points (sufficient to achieve max score) to the final graph. For both *Bear* and *Sam* items accuracy increased from first 4-point graph to final graph [*Bear:* t(197) = 6.3, p < .001; *Sam:* t(126) = 4.9, p < .001].

What differences in strategies may have driven the difference between conditions in accuracy of graphs? To address this question at a broad level we tallied the number of unique graphs produced for both items by counting each step visit in which the student created, deleted, or moved a point (Figure 5a). In most cases revisions of graphs were completed by revisiting the graphing step following the feedback step. For the *Bear* item students in the S+N condition made significantly more revisions than students in the S-only condition [t(203) = 3.3, p < .01]; however, by the final graphing item (*Sam*) an opposite trend emerged in which students in the S-only condition revised marginally more often [t(146) = 2.0, p = .05]. We also analyzed the mean time spent graphing each item by summing duration across all step visits (Figure 5b). For the *Bear* item, differences in conditions reflect number of unique graphs: students in the S+N spent more time graphing than students in the S-only condition [t(203) = 4.1, p < .001]; however, no differences emerged on the *Sam* item.

Perhaps due to the large discrepancy on time for the *Bear* item, more students in the S+N condition who began the *Bear* item did not attempt the *Sam* item than in the S-only condition [S+N: n = 42; S-only: n = 19; $X^2(1) = 8.7$, p < .01]. This attrition is reflected in the different degrees of freedom reported in previous analyses. Of the students remaining by *Sam* there were no differences between groups on pretest "The Race" scores [t(186) = 0.05, p > .1], suggesting that these groups were equivalent in terms of prior knowledge.

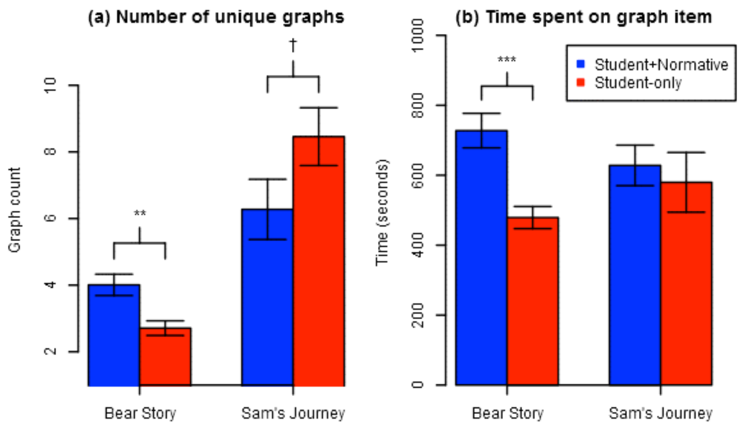

Figure 5. Comparisons of number of unique graphs (a) and time spent on graphing items (b) by condition.

Case Studies

The summary measures discussed above indicate that initially (i.e., on the *Bear* item) students in the S+N condition spent more time graphing and viewed feedback more often than students in the S-only condition. We analyze specific cases from log data to demonstrate how initial student ideas and the affordances of the graphing tools impacted graphing strategies. Cases were selected from a subset of students who showed improvement from pretest to posttest to illustrate how the graphing activity may have supported learning.

For pair A, in the Student-only condition, both students' incorrect response to "The Race" pretest item revealed a misunderstanding of the relationships between slope, direction and speed. Figure 6 displays a series of plots that this pair produced for the *Bear* item, initially (plot 1) and following feedback (plots 2-8). While the initial plot does include a segment representing "moving back" with a negative slope, this may not have been purposeful. In the 2nd through 7th attempts the pair tests multiple ideas about how to represent "moving back", including segments that progressed backwards in time (plots 3 and 5). While the final plot correctly represents "moving back", it misses a subsequent "resting" segment; however, this was congruent with their preceding tabular representation, which also missed this feature of the narrative.

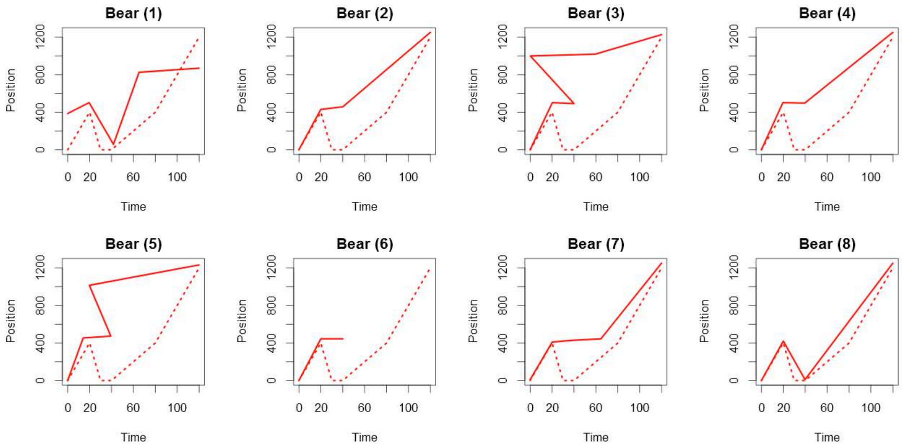

Figure 6: Pair A, *Bear* graphing item, S-only condition. Solid lines indicate student-constructed graph. Dotted lines indicate normative graph (students did not view this graph).

Likewise, Pair B (Figure 7) in the S-only condition also missed several key features of the narrative in their table: neither "moving back" nor "resting." While this pair took a successful iterative approach to represent data in their table, by missing relevant features in the table this pair lost the opportunity to test ideas about how to represent "moving back." However, in a subsequent, simpler narrative ("forward-back") these students were able to recognize their mistake and construct an appropriate graph.

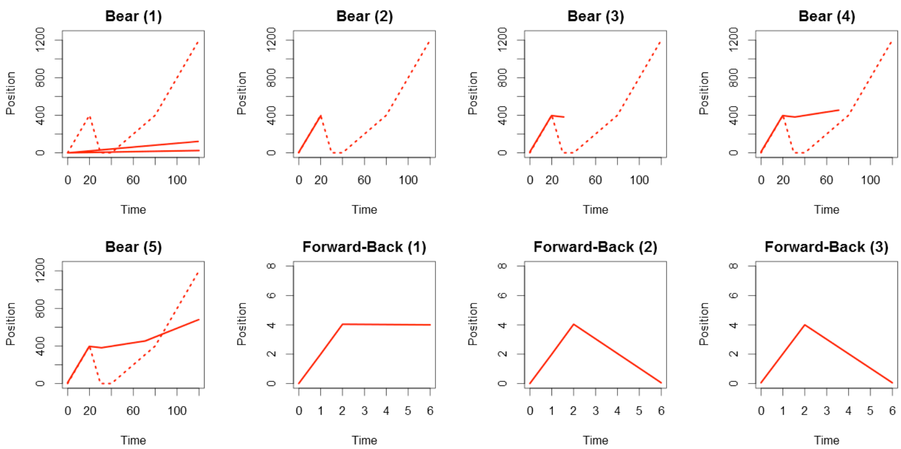

Figure 7: Pair B, *Bear* graphing item and *Forward-Back* graphing item, S-only condition.

In these two examples students were able to produce graphs that (nearly) accurately depicted the information in their tabular representations. Therefore the animation that these students viewed likely fit their interpretation of the narrative. This prevented these students from recognizing missing features of their graph. On the other hand, the *S+N* condition feedback was not dependent on students' interpretation of the narrative in advance of viewing feedback, thereby affording easier evaluation of graph accuracy.

For pair C (Figure 8), these students produced a graph (plot 4) with a transposed resting and backwards segments, as well as a missing final speed change. Because, in this case, the students produced a correct table prior to graphing, the errors in plot 4 likely represent a simple mistranslation of the tabular data. While the resulting animation would be discrepant from the narrative, the difference – particularly in regards to the speed change – would be subtle. Yet, with the addition of the normative animation the discrepancy is clear. In this case the pair recognized the errors and successfully revised their graph (plot 5).

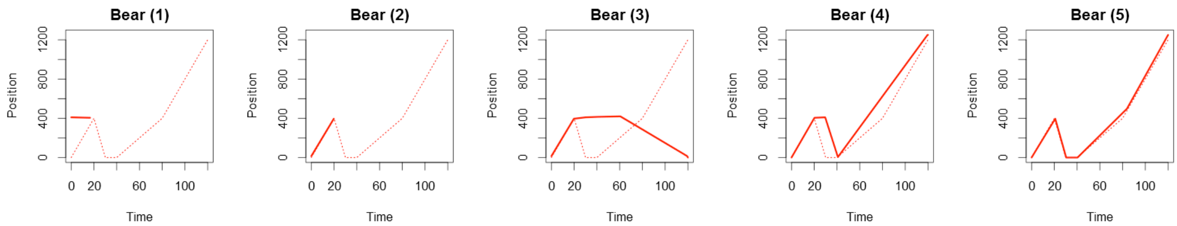

Figure 8: Pair C, *Bear* graphing item, S+N condition.

The S+N condition, however, also has the unanticipated consequence of supporting a process of trial-and-error to achieve an accurate result. For example, Figure 8 shows 8 of 15 unique graphs that pair D produced in the *Bear* item. While these students understood how to represent both "moving back" and "resting" events graphically as shown in their early graphs, they appear to use the affordances of the feedback to rapidly guess and check, without deliberate planning, to complete the speed change feature of their graphs.

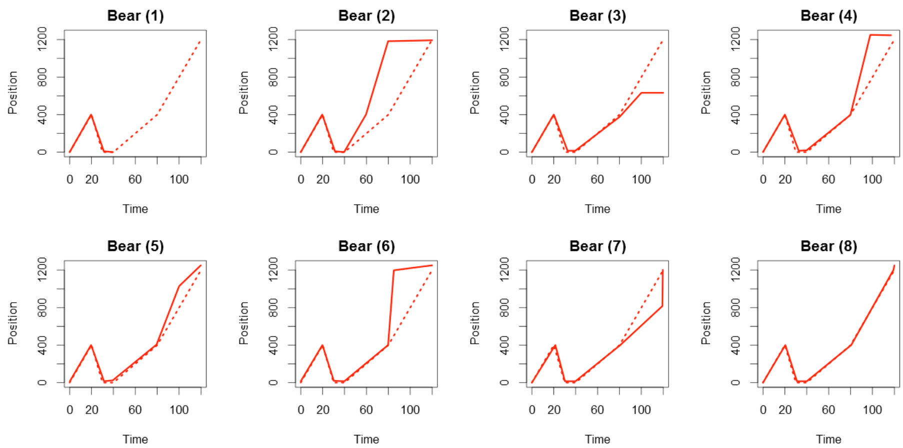

Figure 9: Sample of Pair D plots, *Bear* graphing item, S+N condition (7 plots removed).

Conclusions and Implications

While graphing instruction is often situated in an abstract mathematical context, students need to interpret quantitative data represented in graphs in multiple professional fields and everyday life. Thus, activities such as constructing graphs from a narrative provide students with an opportunity to engage in authentic professional practices. Additionally, by situating activities in personally-relevant contexts we invite students to make connections between formal concepts addressed in school and everyday experiences.

The *Graphing Stories* curriculum unit in WISE has been designed and refined with the collaboration of multiple expert teachers and researchers to help students develop ability to link narratives to graphs and graphs to narratives. The curriculum seeks to help students test and refine their ideas and to develop the ability to interpret graphs in new complex situations. Technology can help students add new ideas and also engage in the complex and difficult task of distinguishing between and reflecting on multiple ideas (Linn & Eylon, 2011).

While dynamic visualizations are common in online tools, this investigation reveals that students need extensive opportunities to test and refine their ideas with guidance that helps them sort out conflicting interpretations. When instruction promotes distinguishing between predicted and actual outcomes of a visualization students are more likely to revise their own thinking. The manner by which technology supports distinguishing is an important subject of learning sciences research. We encourage additional research that builds on these findings.

In this study the Student-only [single] condition supported evaluation of an animation in reference to the imagined sequence of the narrative. This required the student to establish a clear interpretation of the sequence. As the case studies demonstrate, when students misinterpreted important sections of the narrative, as revealed by the table, the feedback did not promote revision. On the other hand, the Student+Normative [dual] condition alerted students of an error independently of their understanding of the narrative. In some cases this affordance led students to adopt a trial-and-error strategy that circumvented more rigorous planning.

While we suspect that the similarity in posttest gains between groups is partially due to the tradeoffs illustrated in the case studies, there are several alternative explanations that require future research. First, it may be the case that over the course of six learning activities students in both conditions achieved a personal ceiling on the material. This is demonstrated by the initial and final graphs for the *Sam* item. While students in the Student-only condition arrived at the item more prepared to construct accurate graphs initially, their final graphs were generally of equal quality as those in Student+Normative condition. Future research will explore more complex tasks.

While neither condition showed a clear advantage we suspect that some mix of dual and single animations would be beneficial. Specifically, while the normative animation could represent an initial scaffold for early items, it could be removed in later activities to help students develop new strategies. Additionally, alternative forms of feedback (e.g. text), in conjunction with the student animation, could facilitate evaluation and planning for graph revisions. More generally, this study represents an important direction for learning sciences research on the use of visualizations to advance graph understanding. While visualizations are a valuable tool for conveying ideas, the specific features and affordances require critical analysis. As the case studies presented here illustrate, emergent student strategies are often surprising and ultimately informative.

References

Black, J. B., Segal, A., Vitale, J. M., & Fadjo, C. L. (2012). Embodied cognition and learning environment design. In D. Jonassen & S. Land (Eds.), *Theoretical foundations of learning environments* (2nd ed., pp. 198–223). New York: Routledge.

Cope, P., & Simmons, M. (1994). Some effects of limited feedback on performance and problem-solving strategy in a logo microworld. *Journal of Educational Psychology*, *86*(3), 368–379.

Imhof, B., Scheiter, K., Edelmann, J., & Gerjets, P. (2013). Learning about locomotion patterns: Effective use of multiple pictures and motion-indicating arrows. *Computers & Education*, *65*, 45–55.

Leinhardt, G., Zaslavsky, O., & Stein, M. K. (1990). Functions, graphs, and graphing: Tasks, learning, and teaching. *Review of Educational Research*, *60*(1), 1–64. doi:10.2307/1170224

Linn, M. C., & Eylon, B.-S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. New York: Routledge.

Mayer, R. E. (2001). *Multimedia learning*. New York: Cambridge University Press.

Mokros, J., & Tinker, R. (1987). The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching*, *24*(4), 369–383.

Moreno, R. (2001). Designing for Understanding□: A Learner-Centered Approach to Multimedia Learning. *Cognition*, (1999), 248–250. Retrieved from http://www.unm.edu/~moreno/conferences.htm

National Governers Association Center for Best Practices, C. of C. S. S. O. (2010). *Common Core State Standards*. Washington, DC: National Governers Association Center for Best Practices, Council of Chief State School Officers.

Ploetzner, R., Lippitsch, S., Galmbacher, M., Heuer, D., & Scherrer, S. (2009). Students' difficulties in learning from dynamic visualisations and how they may be overcome. *Computers in Human Behavior*, *25*, 56–65.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., & Duncan, R. G. (2004). A scaffolding design framework for software to support science inquiry. *The Journal of the Learning Sciences*, *13*(3), 337–386.

Roschelle, J., Kaput, J., & Stroup, W. (2000). SimCalc□: Accelerating students' engagement with the mathematics of change. In M. J. Jacobson & R. B. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 47–75). Lawrence Erlbaum Associates.

Ryoo, K., & Linn, M. C. (2012). Automated feedback in a computer-based diagramming tool to help students distinguish among energy ideas in life science. In *Poster presented at the annual meeting of the American Education Research Association in San Francisco, CA*.

Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. *Educational Psychology Review*, *14*(1), 47–69.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*, 257–285.

Vitale, J. M., Black, J. B., & Swart, M. I. (2013). Applying grounded coordination challenges to concrete learning materials: A study of number line estimation. *Journal of Educational Psychology*, *Advance on*.

Zhang, J., & Norman, D. A. (1994). Representations in distributed cognitive tasks. *Cognitive Science*, *22*, 87–122.