The Challenges of "Bottleneck Graphs" in the Earth Sciences: Evidence from Expert and Novice Eye-Tracks

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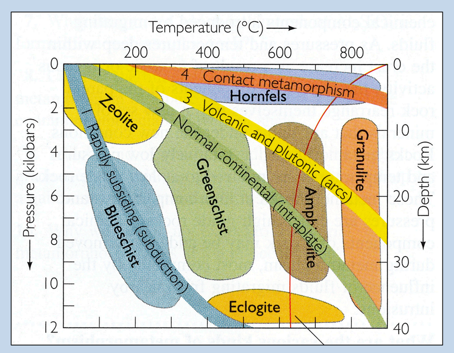
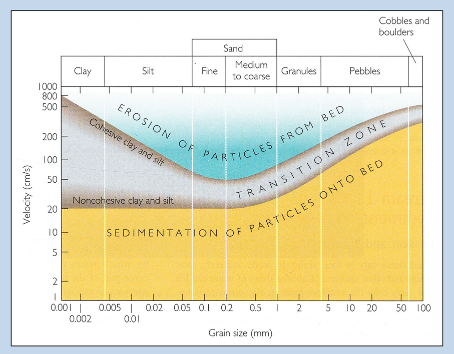
Abstract

Earth scientists make use of a number of unique types of graphical formats that facilitate the representation and interpretation of data. These graphs present significant challenges to students learning but—once mastered—can foster new learning. In this companion poster presentation (see Lindgren and Wirth, this volume), we compare the eye-tracks of experts and novices when observing "bottleneck" graphs.

We observe ordinal differences in eye-fixations between individuals in novice (undergraduate student) and expert (faculty and staff) groups. When asked to examine a graph without a prompt, the expert behavior is consistently systematic and deliberate, while the novice behavior is not. When novices and experts observe traditional binary line or scatter graphs under prompted conditions, the eye-tracks of individuals from both groups look more similar. Interestingly, the eye-track patterns of the individuals in the novice and expert groups diverge in response to non-traditional graph types (e.g., inverted binary plots, normalized plots, ternary plots). The comprehension accuracy of "bottleneck graphs" distinguishes those experts with heightened graphical capacity (regular disciplinary graph use) from those experts with "adaptive expertise" (those who do not regularly use graphs in their discipline). One explanation is that experts, with generally better-developed metacognitive or critical thinking skills, might be able to compensate for lack of familiarity in reading and comprehending new kinds of graphical information.


Press & Siever (2001)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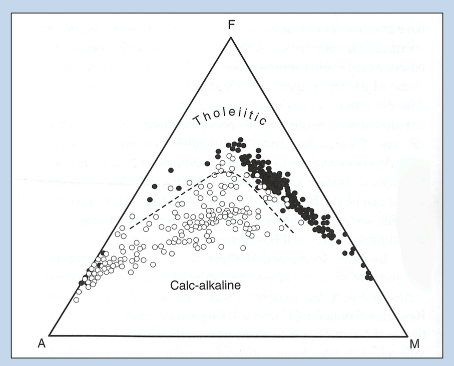
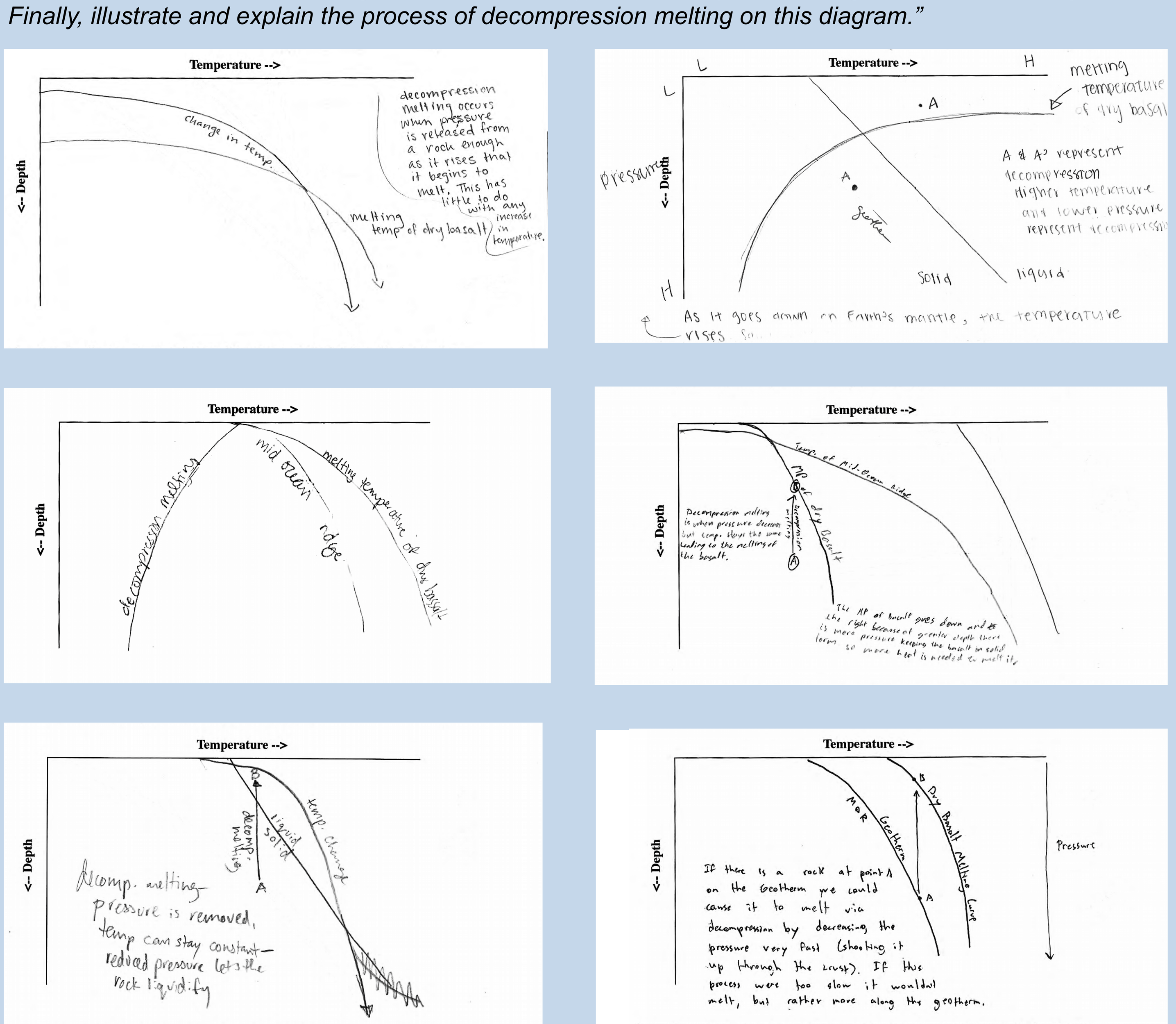

Winter (2010)

Graph Skills & Bottlenecks in Earth Sciences

- The ability to use and interpret graphs for decision-making is an important science literacy skill (Shah and Hoeffner, 2002; Glazer, 2011) and needs to be taught explicitly (Dreyfuss and Eisenberg, 1990)
- Evidence from research (Friel et al., 2001; HyOnA, 2010; Genefurtner et al., 2011) and our own students' work suggests that many students in introductory earth science courses have relatively low-level understandings (e.g., recall) of graphs
- The wide variety of novel graph formats that are utilized in earth science courses introduce additional cognitive loads (Shah and Carpenter, 1995) during learning
- If we hope to improve instruction of graph skills, we first need to better understand how novices and experts interact with graphical information

Exam Prompt and Representative Student Responses:
"In the temperature versus pressure diagram below, illustrate the change in temperature that occurs with depth beneath a mid-ocean ridge. Also indicate (with a curve) the melting temperature of dry basalt. Finally, illustrate and explain the process of decompression melting on this diagram."



Example student responses to exam prompt. Students encountered this diagram in both readings and in class. However, most students, including those who could explain the concept of decompression melting, could not illustrate the relationship between temperature and depth in the Earth.

Eye-Tracking Experiment

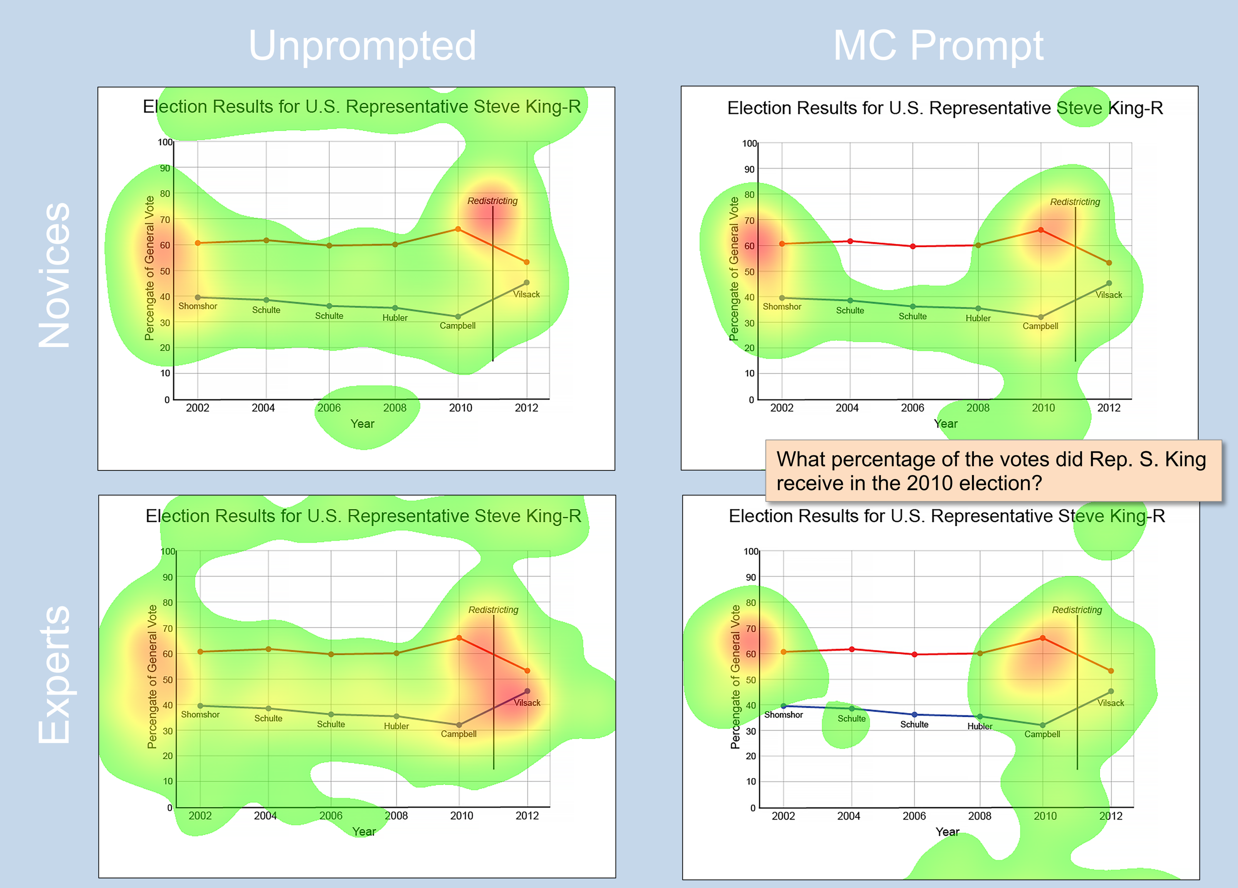
- Experimental graphs were designed to be similar to common geoscience graph formats, but with non-disciplinary content.
- Thirty-eight novices (students from all disciplines) and twenty-five experts (faculty and staff from all disciplines) viewed graphs under unprompted conditions, then responded to questions at three different levels (description, interpretation, and prediction; after Friel et al., 2001)
- Eye-track data were recorded using an EyeLink 1000 eye-tracking device (SR Research Ltd)

Traditional Binary Graph

- Heat maps (below) of the aggregate eye-tracks of novices and experts under unprompted and prompted conditions are similar, but with significant differences. Expert fixations include more of the x-axis and the data trend; novices fixated more on the label (unprompted condition) and irrelevant data (prompted)
- Expert responses to questions were significantly more accurate than those of novices at all levels (right)

Accuracy of Responses

Question Level	Novices	Experts
Multiple-Choice Score	0.8 (± 0.1)	0.9 (± 0.1)***
Interpretation Accuracy	4.0 (± 0.8)	4.5 (± 0.9)***
Prediction Accuracy	3.6 (± 1.1)	4.4 (± 0.9)***

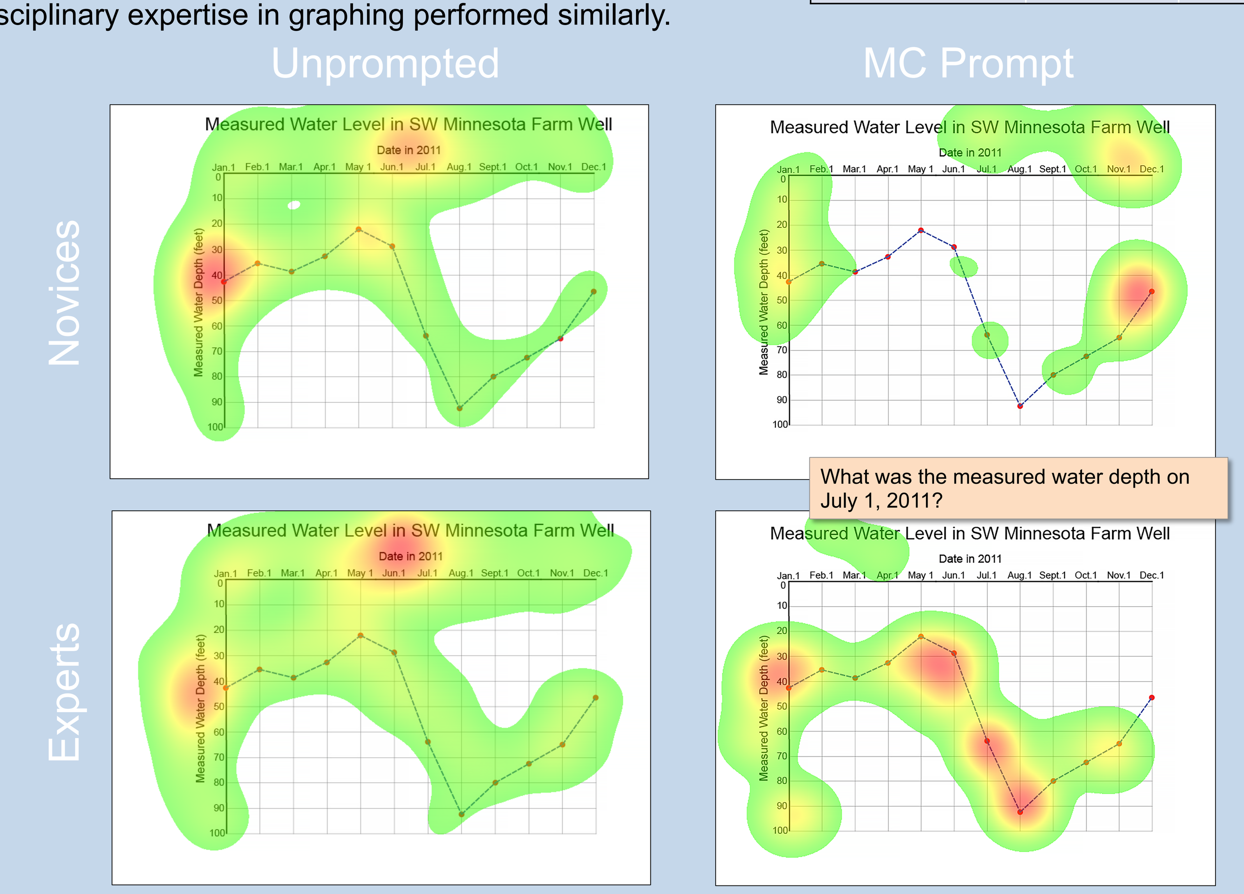


Inverted Binary Graph

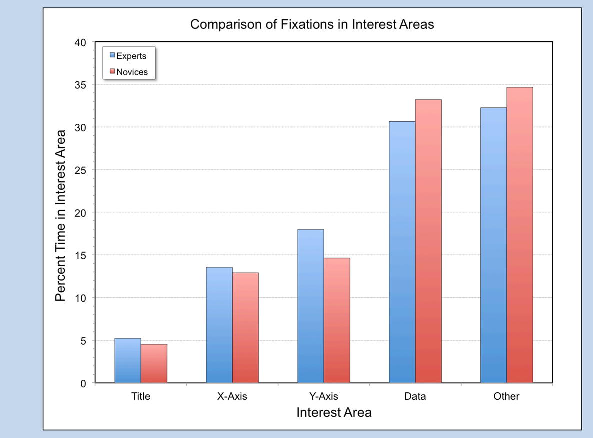
- Novice and expert eye-tracks exhibit greater differences during both the prompted and unprompted conditions (below); experts focused more on data and x-axis; novices focused more on the y-axis
- Expert responses were significantly more accurate than those of novices at all levels (right), and the gap between the two groups was larger than in the traditional formats
- Despite the novel graph format, experts with and without disciplinary expertise in graphing performed similarly.

Accuracy of Responses

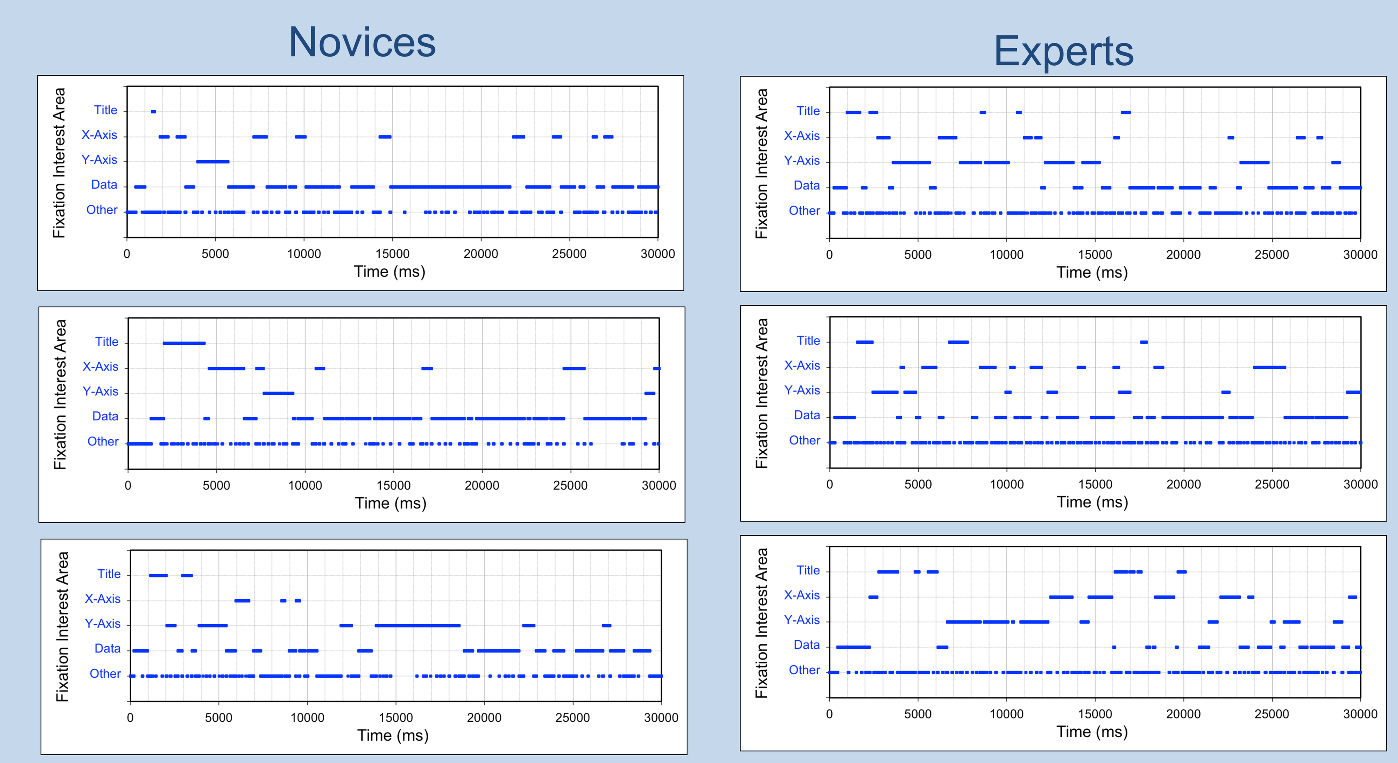
Question Level	Novices	Experts
Multiple-Choice Score	0.7 (± 0.1)	0.9 (± 0.1)***
Interpretation Accuracy	3.5 (± 1.0)	4.3 (± 1.0)**
Prediction Accuracy	3.3 (± 0.9)	4.2 (± 0.9)**



Discussion



- Despite having similar eye-track heat maps, experts consistently out-perform novices. What do they do differently?
- The amount of time that both groups spend fixated in the different interest areas is similar, but experts on average spend more time looking at the title, and axes (right)
- When the fixation locations are viewed in their time sequence, we see that expert fixations alternate between title, x-axis, y-axis and data, even after an initial orientation period (below)



Example time-series plots of eye-track fixations for novices and experts under unprompted conditions while observing the inverted binary plot. Note that both novice and expert fixations move quickly among the different graph elements during an initial orientation phase (10-15 seconds). Experts also commonly continue to alternate fixations between data and axes during the later stages of the observation period (10-30 seconds) whereas novice fixations tend to focus mostly on the data area. Similar patterns are also seen in the time-series plots of aggregate interest area fixations.

Conclusions

- The expert-novice categorization of the study population yields the highest correlation with response accuracy
- Within the novice population, the only demographic variable that correlates with response accuracy is the number of science and math courses completed. Apparently, we are making a difference!
- Within the expert population, there are no significant differences, regardless of disciplinary expertise
- Novice and expert populations have distinct eye movement patterns while viewing graphs
- Experts eye-tracks record continuous movement among the different interest areas, and are characterized by movements between the data and axis elements of graphs suggesting that they actively engage in self-directed and strategic exploration as they seek to make meaning of the data, even while under un-prompted conditions. These observations are consistent with those of previous studies of how people interact with graphs and maps (Clark et al., 2009; HyOnA, 2010); Gegenfurtner et al. (2011).
- Combined with evidence from "talk-alouds" during experimental sessions, we believe that experts, who generally have better developed metacognitive and critical thinking skills, more regularly engage in hypothesis testing, monitoring and self-questioning while viewing graphs, and that these skills may help to compensate for lack of familiarity with novel kinds of graphical information.
- Graph instruction should include explicit instruction and modeling of the self-regulatory processes utilized by experts

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Acknowledgements

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