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Scaffolds to Advance Revision in Science: Meta-Cognitive Knowledge About Revision Versus Generating Content Understanding

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Abstract: We examined whether knowledge about how to revise an explanation or opportunities to deepen content understanding support learners to revise their explanation of a complex science phenomenon. Learners in grades 6 to 10 (N = 147, M_{age} = 13.20, *SD* = 0.74) completed an online unit on Global Climate Change and were randomly assigned to one of three conditions (meta-cognitive scaffold, content scaffold, control condition without scaffold). An ordinal mixed-effects regression model showed that learners in the three conditions did not differ substantially in the quality of their revisions. An exploratory analysis indicated that whereas in the meta-cognitive condition the quality of learners' revisions was not related to their domain-specific prior knowledge, in the content scaffold and control conditions learners with higher prior knowledge produced better revisions. We discuss implications of these findings for practicing revision in science education and for future research.

Objective

Revision involves reviewing previously completed work and making changes to increase the completeness and accuracy of that work (Brownell et al., 2013; Tansomboon et al., 2017). When learners revise their explanations, they think more deeply about the learnt concepts which improves their understanding (Fitzgerald, 1987). Revising helps learners integrate their prior and newly learnt knowledge; a key aspect of forming coherent understanding (Linn et al., 2003). Scientists constantly engage in revision to improve their explanations of scientific phenomena, but students generally resist revising (Trevors et al., 2016). Often due to a lack of teachers' time, students also do not receive ample opportunity to engage in revision as a scientific practice during formal education (Beal et al., 1990). When asked to revise, students make superficial revisions like adding one word, or correcting grammar mistakes (Roscoe et al., 2013). When scaffolded, however, students make substantive revisions, such as elaborating an idea, adding new ideas, or correcting inaccuracies; this improves their explanations and consequently their understanding (Gerard & Linn, 2016; Roscoe et al., 2013). What is not yet understood is the exact effect that different types of scaffolds have on learners' revision behaviours. The present study investigated the relative effects of a meta-cognitive and a content scaffold compared to simply prompting learners to revise their explanations. It discusses the pedagogical reasons underlying the design of these different revision scaffolds to uncover whether learners benefit more from learning how to revise or from deepening their content understanding. Further, this study explores whether the benefit of different types of scaffolds depend on what a learner already knows.

Scaffolding revision of science explanations

Prior evidence

Previous research tested the effects of scaffolds such as critiquing others' work (Donnelly et al., 2015; Schwendimann & Linn, 2016), self-critiquing (Beal et al., 1990), revisiting evidence (Donnelly et al., 2015; Tansomboon et al., 2017), receiving peer or teacher feedback, making comparisons between one's own and an expert's work (Schwendimann & Linn, 2016), planning revision (Tansomboon et al., 2017), learning about revision strategies (Roscoe et al., 2013), and receiving additional domain-specific instruction (Gerard & Linn, 2016). Positive effects of scaffolds on revision were found in terms of the types of revisions learners made (superficial versus substantial) (e.g., Tansomboon et al., 2017) as well as in terms of improvements in the content from initial to revised explanations (e.g., Gerard & Linn, 2016).

Content and meta-cognitive revision scaffolds

One noticeable difference in the scaffolds designed to support learners' revision is that some scaffolds focus on supporting learners to understand the content in more detail while other scaffolds focus on supporting learners to understand what revision entails. For example, revisiting an animation to gain more detailed understanding of the scientific phenomenon that is to be explained can be viewed as a content scaffold (e.g., Donnelly et al., 2015). One reason for designing content scaffolds is to encourage learners to discover new aspects of a phenomenon, or new evidence to add to their initial explanation (Harrison et al., 2018). A simple prompt such as "Please review your explanation" may not be effective because learners most probably do not know what was missing in their initial explanation. In contrast, when guidance encourages learners to revisit evidence they used, they are more likely to generate new ideas that they can add to their explanation. Content scaffolds are also designed to support learners to discover discrepancies between their own explanation and other learning materials. For example, when learners critique a peer's explanation, they might notice that their peer misses a central piece of evidence or describes the phenomena inaccurately (e.g., Schwendimann & Linn, 2016). By providing feedback to the peer and then revising their own explanation, learners might check their own explanation against the advice they gave to the peer.

Although there is evidence that content scaffolds improve learners' understanding, teaching or revisiting content alone does not necessarily mean learners can recognize errors in their initial explanation (Ohlsson, 1996). Learners may need support to contrast their new and old ideas in order to recognize initial inaccurate ideas, refine and integrate them with the new ideas (Linn & Eylon, 2011), instead of just tacking on new ideas to the initial explanation (Harrison et al., 2018) while maintaining their inaccurate initial idea (Campbell et al., 2016; Clark, 2006; diSessa & Minstrell, 1998). This means that learners might not only need new ideas to make substantial revisions, but they also need strategies of how to revise their explanation (Roscoe et al., 2013). Meta-cognitive scaffolds are designed precisely to support learners to understand what they should or can do when asked to revise. Considering that learners do not often get the chance to revise their work (Beal et al., 1990), they might be unfamiliar with the process of revision. They might not know that they could search for errors by comparing their ideas with new evidence. Meta-cognitive scaffolds can provide strategies or give learners the chance to plan their revision (Roscoe et al., 2013; Tansomboon et al., 2017). For instance, worked examples are scaffolds that seem to lend themselves particularly well to fostering knowledge about revision. They have been used successfully to foster knowledge about argumentation by modeling the structure of an argument (Schworm & Renkl, 2007) and knowledge about how to collaborate by modeling collaborative sequences (Rummel et al., 2009).

The role of prior knowledge

Evidence implies that scaffolds need to align with learner's prior knowledge to be effective (Kalyuga, 2007; Snow & Lohman, 1984). Whether learners need deeper content understanding or knowledge of how to revise may depend on their prior knowledge. One could argue that a learner with less prior knowledge may not benefit from knowing how to revise as they do not have the content knowledge needed to add new ideas to their explanation. Learners with less prior knowledge may rather need to investigate more evidence to discover content ideas they can add. This assumption is based on prior evidence showing that learners with less prior knowledge benefit more from specific rather than general guidance (e.g., Renkl, 2014). For learners with more prior knowledge this would mean that they may rather benefit from meta-cognitive scaffolds that support them to refine their approach to revision as they already have the content knowledge needed for improving an explanation.

However, one could argue the opposite and assume that learners with less prior knowledge need to know strategies for revising; learning they can add ideas may guide them to seek out new ideas to add to their explanation (Wu et al., 2016). Not knowing what to do when revising might leave them attending to irrelevant aspects or ideas consistent with their explanation.

Additionally, previous research proposes that the level of engagement required by a scaffold will influence how learners with differing prior knowledge benefit from the scaffold. According to the ICAP Framework, activities which actively engage learners and encourage the manipulation of new information support learners who have less prior knowledge, whereas activities which encourage constructive engagement and knowledge generation better support learners with high prior knowledge (Chi & Wylie, 2014). Thus, whether a meta-cognitive or content scaffold is more effective for learners with less or more prior knowledge may depend on the scaffolds' affordances i.e., whether learners are engaged actively or constructively.

Research questions and hypotheses

We build on prior research and contribute to what is known about effectively guiding revision by experimentally testing what effect a meta-cognitive scaffold and a content scaffold have compared to a simple prompt to revise on learners' revision of a science explanation. We expect that students in the the meta-cognitive or content scaffold condition make more substantial revisions than students who are not supported (control condition).

Furthermore, we explore whether the effect of the meta-cognitive and content scaffold depend on learners' prior knowledge. Based on the discussed theories that point towards effects in either direction, we have no specific hypotheses as to whether the meta-cognitive or content scaffold is more effective for learners with less or more prior knowledge. In addition, we explore what students understand by the term revision in a qualitative analysis of student responses.

The present study including hypotheses and analysis plan was preregistered prior to the analyses on the Open Science Framework (OSF) (osf.io/yxa2k/). The learning unit used in this study, the coding schemes used to assess learners' knowledge and revision, and an anonymized data set including a variable documentation are openly shared on OSF once this paper is published.

Methods

Sample, design, and procedure

Four science teachers (one woman, three men) and their $N = 147$ learners (73 girls, 54 boys, 20 did not or preferred not to answer; $M_{age} = 13.20$ years, $SD = 0.74$) at secondary schools in the UK and Georgia participated in the study. These countries were used for recruitment because of researchers' familiarity with the education systems and/or the specific schools contacted. No compensation was given for participation. Data was used if the student and parent gave consent (UK) or if the student gave consent and parents did not object (Georgia). Researchers only had access to anonymized student data.

After applying exclusion criteria (detailed in results), a sample of $N = 66$ learners were included in statistical analyses (n = 50 in 8th, n = 16 in 6th – 10th grade). We used an online learning unit on Global Climate Change from the Web-based Inquiry Science Environment (WISE; Linn et al., 2003) and randomly assigned learners to one of three conditions: meta-cognitive scaffold (n = 24, 10 boys, 13 girls, $M_{age} = 13.09$, $SD = 0.75$), content scaffold (n = 19, 11 boys, 8 girls, $M_{age} = 13.41$, $SD = 0.71$), or control condition (n = 24, 9 boys, 14 girls, $M_{age} = 13.15$, $SD = 0.75$).

The study was administered slightly differently by each teacher, as teachers were free to choose the time frame of unit completion (ranged between 2 – 4 weeks), learners completed the unit at home on a device of their choice, and completion of the unit was voluntary. All learners received information about the study, were guided by teachers to create WISE accounts and log in to the unit, completed a pretest and then the unit.

Learning materials and scaffold conditions

The Global Climate Change unit covers how types of energy from the Sun transform and warm the Earth, how energy from the Sun interacts with greenhouse gases, and the greenhouse effect. Students explore how the human impact on the natural balance of greenhouse gases affects global temperatures and climate change. Students are engaged through various techniques: direct instruction, making predictions, observing evidence in interactive models, checking understanding with automated feedback, choosing variables of interest to investigate further, and writing explanations. Mid-way through the unit, learners were asked to "explain to Lea what role greenhouse gases play in how the Sun warms the Earth." Learners wrote an initial explanation and revised that explanation after the scaffold activity; in the revision step, an editable version of the initial explanation was imported.

Meta-cognitive scaffold

We designed a double content worked example, which guided learners step-by-step through 3 distinct revision steps: (1) adding ideas; (2) changing ideas; and (3) integrating ideas (Tansomboon et al., 2017). The example modeled the learning domain (revision strategies) using photosynthesis as the exemplifying domain (Schworm & Renkl, 2007). Learners could follow the thought process of a fictitious student James via thought bubbles that visualized James' thinking. The worked example modeled each revision step (add, change, integrate) and how James applied this step to his explanation about photosynthesis by highlighting the changes he made to his explanation (Figure 1). In the last step of the example James encouraged learners to revise their own explanation the same way he had revised his. Learners could move through the self-paced worked example multiple times.

Content scaffold

In an interactive workspace, learners dragged and dropped icons labelled 'Sun', 'Space', 'Surface of the Earth', 'Below the surface of the Earth', and 'Greenhouse Gases'; then added arrows to demonstrate the flow of energy between the elements in their diagram. Each arrow could be labeled with a type of energy ('solar energy', 'heat energy', 'infrared radiation'). When learners submitted their energy flow diagram, immediate, automated knowledge integration guidance was provided, which highlighted an inaccurate or missing aspect of the learner's diagram and directed them to revisit specific learning activities in the unit (Vitale et al., 2016). For example, when a learner inaccurately modeled that solar radiation was emitted from the surface of the Earth, the guidance prompted: "What type of energy is this? Where does it come from? Go back to the simulations in Step 1.6 and 1.7 to find out!" Learners were instructed to work on their diagram until they were told "Good job!", but learners could themselves move on whenever they wanted. They could submit their diagram and receive automated feedback multiple times (see Figure 2).

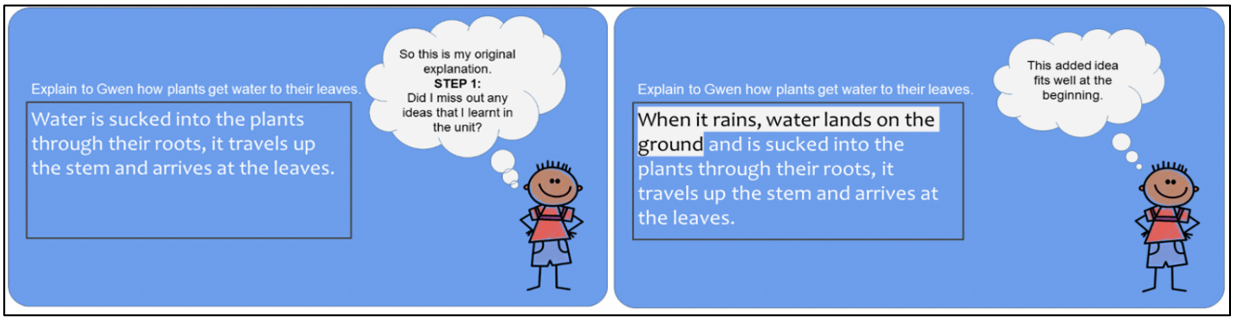

Figure 1. Meta-cognitive revision scaffold, modeling the revision step "adding ideas" via the exemplifying domain photosynthesis in a double content worked example.

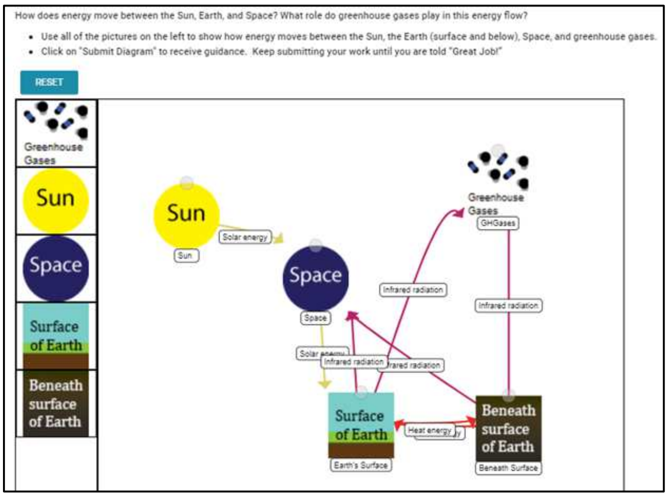

Figure 2. Content revision scaffold, demonstrating a learner's energy flow diagram.

Control condition

Learners saw an editable version of their initial explanation and were prompted to revise with this prompt: "When we explain, we often don't include all our ideas. We often also realize that we didn't fully understand something when trying to explain it. Scientists often revise their work to refine their ideas and strengthen their explanations. This is your explanation to Lea. Think about whether you actually know more than you have written down and have a go at revising your initial explanation!"

Measures

To measure revision, we developed a rubric that assessed the type of change made from learners' initial to revised explanation (Table 1). The rubric was adapted from prior research (Tansomboon et al., 2017). We first coded the initial explanation with a knowledge integration (KI) rubric and when the initial explanation received the highest score (5), we assumed that no condition would have an effect as there was no change the learner could make to improve their explanation. Initial explanations that received a KI score of 5 were excluded from the analyses. Two researchers coded 10% of all initial and revised explanations independently, resolved disagreements in discussion, and iterated this process until Cohen's kappa was > .8. Then one trained researcher coded all data. The dependent variable revision is treated as ordinal variable in our statistical analysis as the rubric only allows ranking of the types of revision learners made.

We measured learners' prior knowledge about climate change with five open response items, for example: "*Nina learned that life on Earth - humans, animals, and plants - can survive because the Earth's temperature is not too cold and not too hot. It is just warm enough to maintain life. Why doesn't the Earth overheat* *or get too cold and what could cause its temperature to get warmer and warmer?*" Each of the five items was coded using KI rubrics developed based on prior research (Bichler et al., 2019) that assess how well learners integrate ideas in their explanation (1 = inaccurate, vague or off-topic idea; 2 = accurate but isolated idea, no mechanism explained; 3 = inaccurate, vague, or incomplete mechanism; 4 = accurate mechanism; 5 = accurate and fully elaborated mechanism). Test items were coded as described for revision. A mean score across the five items was used as an indicator of prior knowledge (moderator and control variable).

We measured learners' understanding of the process and purpose of revision by asking them "Explain what you do when revising an explanation" and "What are some important reasons to revise your ideas in science?" Responses to these pretest items were analyzed qualitatively by identifying common themes.

Table 1: Revision rubric

Code	Description	Category of Responses
0	No revision needed	Initial explanation is complete and no changes were made
1	No revision	Initial and revised explanation are the same
2	Superficial revision	Words replaced, spelling errors fixed, or grammar changed Overall idea from the initial to revised explanation stays the same
3	Non-normative revision	Idea from initial explanation changed or elaborated, but idea is inaccurate
4	Substantive revision	Accurate ideas(s) added or inaccurate idea(s) changed to accurate ideas

Results

After excluding learners who did not consent, who had initial explanations with KI score 5, and who did not complete the revision step in the unit, there were $n = 24$ in the meta-cognitive, $n = 19$ in the content, and $n = 24$ in the control condition. After excluding one learner who did not complete the pretest, a sample of $N = 66$ was used for analyses.

Of students in the meta-cognitive scaffold condition, 67% made no revisions, as well as 68% of students in the content, and 71% of students in the control condition. To test our hypothesis that students who are supported with the meta-cognitive or content scaffold make more substantial revisions than students who are not scaffolded (control condition), we used an ordinal mixed-effects regression model. To control for the hierarchical data structure, a random intercept across teachers was added. We included prior knowledge (mean centered) as control variable in the model. We used the control condition as the reference group and included dummy variables for the two scaffold conditions (meta-cognitive and content) in the model. We found no statistically significant difference in revision for the meta-cognitive condition ($b = .59$, $z = .61$, $p = .272$) and the content condition ($b = .04$, $z = .06$, $p = .478$) compared to the control condition. The parameters from the model predict the chance that learners in each condition receive a particular revision score. Across all conditions, there was a low chance that learners substantively revised their explanation and received a revision score of 4, but this was more likely for those in the meta-cognitive condition (10%) than those in the content (6%) or control condition (6%). Learners in the meta-cognitive condition were also more likely to make a non-normative revision (revision score = 3, 22%), than those in the content (15%) or control condition (15%). The model predicted little difference in the chance of learners to revise superficially (revision score = 2) across all three conditions (10-13%). Finally, the chance of making no revision (revision score = 1) was predicted to be lower for those in the meta-cognitive condition (55%), compared to those in the content (68%) or control condition (69%). These model results hint that learners in the meta-cognitive condition were more likely than those in the content and control conditions not only of making a revision, but also of making more sophisticated revisions (non-normative and substantive). As the effects of conditions were not statistically significant, these results should only be interpreted descriptively.

Exploratory analyses

We explored the interaction effects between prior knowledge and the scaffold conditions by adding interaction terms for prior knowledge and meta-cognitive scaffold, and prior knowledge and content scaffold to the ordinal mixed-effects regression model. A visualization of the interaction between learners' prior knowledge and their revision scores in the three conditions is provided in Figure 3. We observed a significant main effect of prior knowledge ($b = 4.94$, $z = 1.86$, $p = .032$), indicating that in the control condition, learners with more prior knowledge showed higher revision scores. We observed a significant negative interaction effect between prior knowledge and the meta-cognitive condition ($b = -7.07$, $z = -2.07$, $p = .019$) indicating that the relation between prior knowledge and revision was less strong in the meta-cognitive condition compared to the control condition. A positive yet non-significant trend was observed in the interaction effect between prior knowledge and the content condition ($b = -3.66$, $z = -1.25$, $p = .106$), indicating that the relation between prior knowledge and students' revision score was also slightly less strong in the content condition than in the control condition.

To examine learner's understanding of the revision process we explored responses ($N = 73$) to the question "Explain what you do when revising an explanation". One researcher read all responses and noted common themes in students' reasoning. Some learners reported not knowing the answer to the question e.g., "I don't know what revising your ideas is supposed to mean". A variety of ideas about what steps to take for effective revision were expressed. For example, clarifying an explanation to communicate ideas better, finding and fixing mistakes, or learners mentioned that revision is a characteristic of "doing good science". Interestingly, the majority of learners understood revision as preparing for an exam. These students described revision as what you do when you revisit or memorize learning materials. For example, one student said "When i revise i make flashcards. i also read the explanation 10 times, say it 10 times and write it 2 times from memory, this helps facts and information remain in my head." We also explored $N = 80$ responses to the question "What are some important reasons to revise your ideas in science?" Learners seem to think that the main reasons to revise are finding and fixing mistakes, improving the quality of communication in science, better preparing for examinations, and staying up to date with the field of science. For example, one learner said, "Revising our ideas in science helps us to catch our mistakes if we made during the process". Another learner said, "To make it easier for other people to understand".

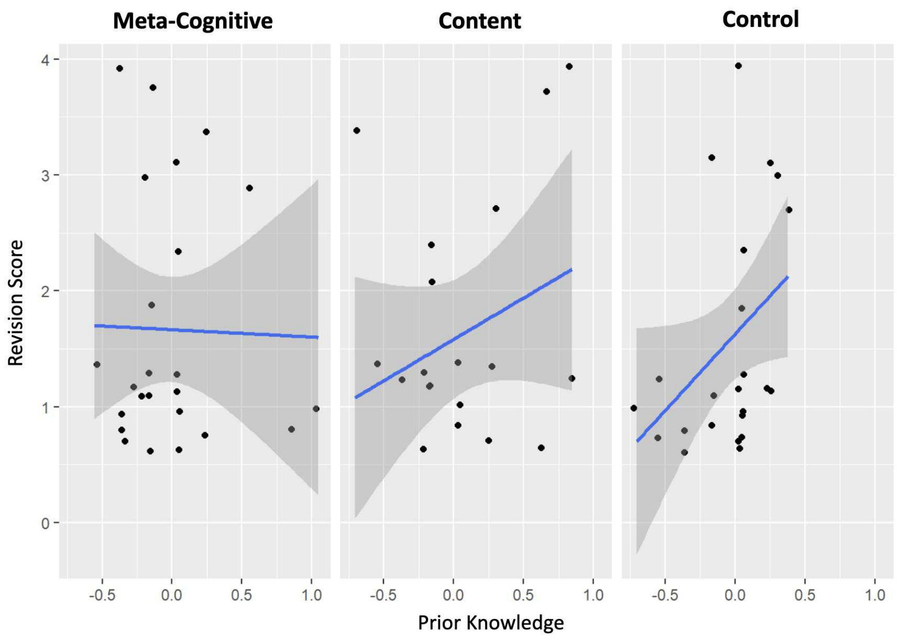

Figure 3. Graph demonstrating the interaction effects between prior knowledge (x-axis, z-standardized) and scaffold condition on revision score (y-axis). In the meta-cognitive condition (left), learners seem to be able to revise independently of their amount of prior knowledge, whereas in the content condition (middle) and particularly in the control condition (right), learners with more prior knowledge produce better revisions.

Discussion

We found that only about a third (31%) of students revised their explanation across all conditions. The remote learning situation and the fact that completion of the unit was voluntary could be the primary explanation for the low number of students who revised. We assume that had learners been in a classroom, their teachers would have encouraged them to put effort into revising their explanations. However, past studies in classroom settings found similar results (Donnelly et al., 2015; Trevors et al., 2016). Thus, we think that another explanation is that students are not socialized into a revision culture as revision is not a common classroom practice.

We found no evidence that the scaffolds led to more substantial revisions than the control condition, which could be due to the fact only a small percentage of students actually revised their explanation across all conditions. However, our control condition prompt may have been more than just asking students if they want to revise. It may have provided a decent explanation of why scientists revise and thus could be considered a meta-cognitive scaffold. A future study should use an even stronger control ("Please revise your explanation"). A trend was observed in the model estimates which proposed that learners in the meta-cognitive condition were more likely to receive a higher revision score, demonstrating more substantive revisions, than learners in the content scaffold or control condition. The explorative analysis of the interaction between prior knowledge and the scaffolding conditions showed that of the learners who did not receive guidance, those with more prior knowledge revised more substantively than those with less prior knowledge. Previous research suggests that learners who have accurate ideas before instruction are better at connecting old and new ideas than those with inaccurate initial ideas (Visintainer & Linn, 2015). We suggest to test this interaction effect with a larger sample.

Descriptively, it also seemed that learners with less prior knowledge made more substantial revisions when in the meta-cognitive than in the control condition, whereas for learners with higher prior knowledge the meta-cognitive versus control condition did not seem to make a difference. Also, learners with higher prior knowledge seemed to revise more substantively in the content compared to the control condition than did learners with less prior knowledge. These trends can only be interpreted on a descriptive level as our sample size was small and the observed trends are driven by a few learners in each condition. However, these trends provide the basis for further investigation of the interaction of prior knowledge and scaffolds for revision.

Potentially, for learners with less prior knowledge learning how to revise may be more beneficial, such that knowledge about revision is more helpful than deeper content understanding (Ohlsson, 1996). Similarly, learners with higher prior knowledge may benefit more from deepening their content understanding with scaffolds that activate their prior knowledge (McNamara et al., 1996) and help them link existing and new ideas.

Considering that the content scaffold required learners to generate a representation of their understanding, the problem-solving demands of this scaffold may have been higher than those of the worked example. In general, learners with higher prior knowledge benefit from scaffolds that require more problem-solving and learners with lower prior knowledge often struggle with high problem-solving demands (Renkl, 2014).

Moreover, the content scaffold likely engaged learners constructively as they were asked to generate knowledge and infer connections between the elements of their concept map (Chi & Wylie, 2014). Hence, it may have been better suited for learners with higher prior knowledge (Kaiser & Mayer, 2019). In comparison, the meta-cognitive scaffold likely engaged learners actively: it required learners to manipulate and apply the information modelled in the example. Therefore, this scaffold may have worked especially well for learners with lower prior knowledge.

Conclusion

We found that students are not likely to revise even when guided. Our results suggest that students know of many reasons why revision is important. Possibly, they are just not used to revising during and for learning. Instruction that emphasizes revision may establish revision as a common scientific practice. We emphasize that due to lack of statistical power this study by itself does not yet provide evidence that allows for a conclusion regarding the relative effectiveness of meta-cognitive and content scaffolds or the interaction with prior knowledge. However, this study provides a starting point for further investigating the question whether knowing about revision or learning new ideas about the phenomenon one explains is needed to revise one's explanation and if what is effective differs for learners depending on their prior knowledge. As revision is not a common practice in classrooms, learners are likely also not introduced to revision strategies. However, this could be particularly important for learners with less prior knowledge in a domain. It is necessary to replicate this study with a larger sample.

References

Beal, C. R., Garrod, A. C., & Bonitatibus, G. J. (1990). Fostering children's revision skills through training in comprehension monitoring. *Journal of Educational Psychology, 82*(2), 275–280.

Bichler, S., Richards, S., Hasenbein, L., Linn, M., & Fischer, F. (2019). Understanding Climate Change Through Collaborative Versus Individual Inquiry With Constructive or Example-Based Scaffolds. In K. Lund, G. P. Niccolai, E. Lavoué, C. E. Hmelo-Silver, G. Gweon, & M. Baker (Eds.), *13th International Conference on Computer Supported Collaborative Learning (CSCL)* (Vol. 2, pp. 668–671).

Brownell, S. E., Price, J. V., & Steinman, L. (2013). A writing-intensive course improves biology undergraduates' perception and confidence of their abilities to read scientific literature and communicate science. *Advances in Physiology Education, 37*(1), 70–79. https://doi.org/10.1152/advan.00138.2012

Campbell, T., Schwarz, C., & Windschitl, M. (2016). What we call misconceptions may be necessary stepping-stones toward making sense of the world. *Science and Children, 53*(7), 28–33.

Chi, M. T., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823

Clark, D. B. (2006). Longitudinal conceptual change in students' understanding of thermal equilibrium: An examination of the process of conceptual restructuring. *Cognition and Instruction, 24*(4), 467–563.

diSessa, A. A., & Minstrell, J. (1998). Cultivating conceptual change with benchmark lessons. In J. G. Greeno & S. R. Goldman (Eds.), *Thinking practices* (pp. 155–187). Lawrence Erlbaum Associates.

Donnelly, D. F., Vitale, J. M., & Linn, M. C. (2015). Automated guidance for thermodynamics essays: critiquing versus revisiting. *Journal of Science Education and Technology, 24*(6), 861–874. https://doi.org/doi.org/10.1007/s10956-015-9569-1

Fitzgerald, J. (1987). Research on revision in writing. *Review of Educational Research, 57*(4), 481–506.

Gerard, L. F., & Linn, M. C. (2016). Using automated scores of student essays to support teacher guidance in classroom inquiry. *Journal of Science Teacher Education, 27*(1), 111–129. https://doi.org/10.1007/s10972-016-9455-6

Harrison, E., Gerard, E., & Linn, M. (2018). Encouraging Revision of Scientific Ideas with Critique in an Online Genetics Unit. In J. Kay & R. Luckin (Eds.), *Rethinking Learning in the Digital Age: Making the Learning Sciences Count, 13th International Conference of the Learning Sciences (ICLS) 2018* (Vol. 2, pp. 816–823). International Society of the Learning Sciences.

Kaiser, I., & Mayer, J. (2019). The long-term benefit of video modeling examples for guided inquiry. *Frontiers in Education, 4*(104), 1–18. https://doi.org/doi.org/10.3389/feduc.2019.00104

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review, 19*(4), 509–539. https://doi.org/10.1007/s10648-007-9054-3

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration. *Science education, 87*(4), 517–538.

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

McNamara, D. S., Kintsch, E., Songer, N. B., & Kintsch, W. (1996). Are good texts always better? Interactions of text coherence, background knowledge, and levels of understanding in learning from text. *Cognition and Instruction, 14*(1), 1–43.

Ohlsson, S. (1996). Learning from performance errors. *Psychological Review, 103*(2), 241–262. https://doi.org/10.1037/0033-295X.103.2.241

Renkl, A. (2014). Toward an instructionally oriented theory of example-based learning. *Cognitive Science, 38*(1), 1–37. https://doi.org/10.1111/cogs.12086

Roscoe, R. D., Snow, E. L., & McNamara, D. S. (2013). Feedback and revising in an intelligent tutoring system for writing strategies. In H. C. Lane, K. Yacef, J. Mostow, & P. Pavlik (Eds.), *Artificial Intelligence in Education. AIED 2013. Lecture Notes in Computer Science* (Vol. 7926, pp. 259–268). Springer. https://doi.org/10.1007/978-3-642-39112-5_27

Rummel, N., Spada, H., & Hauser, S. (2009). Learning to collaborate while being scripted or by observing a model. *International Journal of Computer-Supported Collaborative Learning, 4*(1), 69–92.

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. *Journal of Research in Science Teaching, 53*(1), 70–94.

Schworm, S., & Renkl, A. (2007). Learning argumentation skills through the use of prompts for self-explaining examples. *Journal of Educational Psychology, 99*(2), 285–296. https://doi.org/10.1037/0022-0663.99.2.285

Snow, R. E., & Lohman, D. F. (1984). Toward a theory of cognitive aptitude for learning from instruction. *Journal of Educational Psychology, 76*(3), 347–376. https://doi.org/10.1037/0022-0663.76.3.347

Tansomboon, C., Gerard, L., Vitale, J. M., & Linn, M. C. (2017). Designing automated guidance to promote productive revision of science explanations. *International Journal of Artificial Intelligence in Education, 27*(4), 729–757.

Trevors, G. J., Muis, K. R., Pekrun, R., Sinatra, G. M., & Winne, P. H. (2016). Identity and epistemic emotions during knowledge revision: A potential account for the backfire effect. *Discourse Processes, 53*(5-6), 339–370. https://doi.org/10.1080/0163853X.2015.1136507

Visintainer, T., & Linn, M. (2015). Sixth-grade students' progress in understanding the mechanisms of global climate change. *Journal of Science Education and Technology, 24*(2-3), 287–310.

Vitale, J. M., McBride, E., & Linn, M. C. (2016). Distinguishing complex ideas about climate change: knowledge integration vs. specific guidance. *International Journal of Science Education, 38*(9), 1548–1569.

Wu, H.-L., Weng, H.-L., & She, H.-C. (2016). Effects of Scaffolds and Scientific Reasoning Ability on Web-Based Scientific Inquiry. *International Journal of Contemporary Educational Research, 3*(1), 12–24.