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Causal Pattern Diagrams in Science Texts Support Explanation

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Abstract: Understanding causal models in science texts requires learners to construct a mental model of complex causal relationships despite unfamiliar vocabulary and limited knowledge. Prior studies show presenting diagrams helps learners improve, but little is known about *how* learning improves with causal diagrams. In an online study, we tested adults' explanations of five science phenomena after reading text with or without a schematic causal diagram. The quantitative and qualitative results show causal pattern diagrams promote *holistic quality* in learners' explanations. Providing visualizations of complex causal relationships within science texts can scaffold learning by highlighting the need to understand causal patterns in science.

Introduction

People need to understand causal models to reason about weather, health, and natural events, but science phenomena are challenging for learners of all ages. Causal models explain how natural systems operate as cause-and-effect patterns with directionality, dependencies, and effects (Cook & Mayer, 1988). Understanding a causal model allows novel inferences (Sloman, 2005; Mayer, 2005) going beyond a presented text to new situations (Bruner, 1957). Though expository texts dominate science learning, they offer no standardized structure (e.g., sequential ordering) (Stenning & Oberlander, 1995), leaving learners to struggle in identifying relevant features and relationships (Leopold & Leutner, 2012).

Given these challenges, how does a learner create a *mental model* of a science phenomenon (Johnson-Laird, 1983; Vosniadou & Brewer, 1987)? To understand *lightning*, a learner must explain how a change in one part of a causal system (moisture) leads to change in another (electrical charge) (Mayer, 2014). Causal diagrams in science texts support learning through cues highlighting the organization of information (Mayer, 2005); however, illustrations showing system states also improve comprehension, recall, and problem solving (Mayer & Gallini, 1990; Guo et al., 2020). What do learners need to extract from scientific texts to build a causal model?

Pointing learners' attention towards the *pattern* of causal relationships may help structure causal models. Simplified diagrams support information integration (Butcher, 2006) and more self-explanation during learning (Ainsworth & Loizou, 2003) by making causal structure explicit (McCrudden, Schraw, & Lehman, 2009). In fact, causal diagrams even *without* text allow a more comprehensive understanding of causal sequences (McCrudden et al., 2007). These findings suggest a schematic diagram representing a pattern of causal relationships helps by providing *less* detail about its elements.

Science texts describe causal models with a great deal of detailed information about physical properties, such as where algae are located within a coral reef. However, an abstract causal diagram omits situation-model information (Zwaan & Radvansky, 1998) to highlight causal relationships. Using a simplified version of Pearl's (2000) causal effect diagram, schematic causal diagrams show a generalized structure connecting relevant entities (nodes) through causal relationships (links) (Vosniadou & Brewer, 1992). The results (Figure 1) from similar length texts is noticeably different causal patterns. For example, one combines causes (firefly light) and one a longer linear chain (coral bleaching).

A causal pattern diagram may provide a focus during comprehension of a text description. To explain *why* a phenomenon takes place, a holistic pattern of abstracted causal relationships is required, reducing emphasis on detailed, specific features. Guided by the causal diagram, learners may be better able to construct their own internal model of the causal pattern presented in the text. To explore the efficacy of provided causal diagrams in science learning, we tested their impact on the quality of learners' explanations of science phenomena.

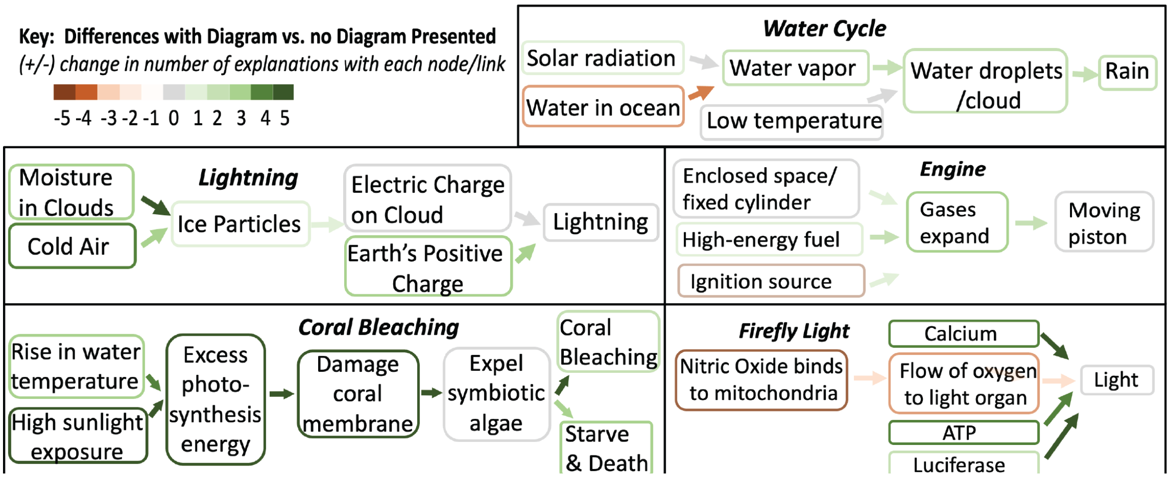
Method

In an online experiment, we presented adults with short science texts describing a causal phenomenon in science. Half read a given text alone and half saw the same text with a provided causal pattern diagram. People then wrote their own explanation from memory, and we compared the qualities of causal models in their explanations.

Participants

Participants (n=127) recruited through Amazon Mechanical Turk completed a short survey for $1.10, including a bonus paid to all. Seven failed the attention check or submitted plagiarized responses and were excluded. The average age was 35.2 (SD = 9.34; range from 19 to 64), and 61% were male. On 5-point rating scales, participants indicated interest in science (M = 1.26; SD = .930) and reading (M = 1.47; SD = .840). Prior knowledge ratings for all five science topics averaged below the scale midpoint of knowing a topic "slightly well."

Figure 1
Summary Diagrams Display the Differences in Nodes and Links Present in Learners' Generated Explanations

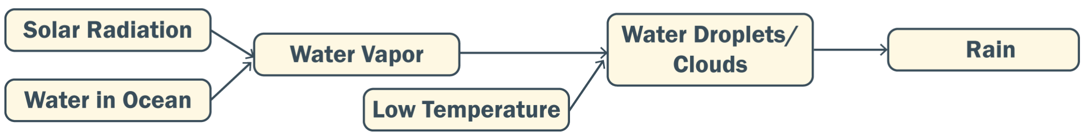


Materials

Five short texts (see Figure 2) from sources such as "Wikipedia," and "How Stuff Works," were edited for conciseness (one paragraph of 129- 226 words, <1 minute reading time). Two experts identified a subset of important idea units in each text with 95% agreement.

Figure 2
An Example Text (causal node descriptions in red and links in blue) with the presented causal diagram

What Causes Rain?
The sun powers the water cycle, moving water from the surface to the air and back down again. Specifically, solar radiation heats ocean water, causing it to evaporate – that is, change phase from liquid to vapor. The water vapor molecule H2O has less density compared to the major components of the atmosphere, nitrogen, and oxygen. Due to the significant difference in molecular mass, water vapor in gas form gains height in the open air as a result of buoyancy. However, as the altitude increases, air pressure decreases and the temperature drops. The lowered temperature causes water vapor to condense into tiny liquid water droplets which are heavier than the air, such that they fall unless supported by an updraft. A huge concentration of these droplets over a large space up in the atmosphere becomes visible as a cloud. These cloud particles collide, grow, and eventually fall out of upper atmospheric layers as precipitation. Some precipitation falls as snow or hair, but most water falls back into the ocean and land as rain.



Procedure

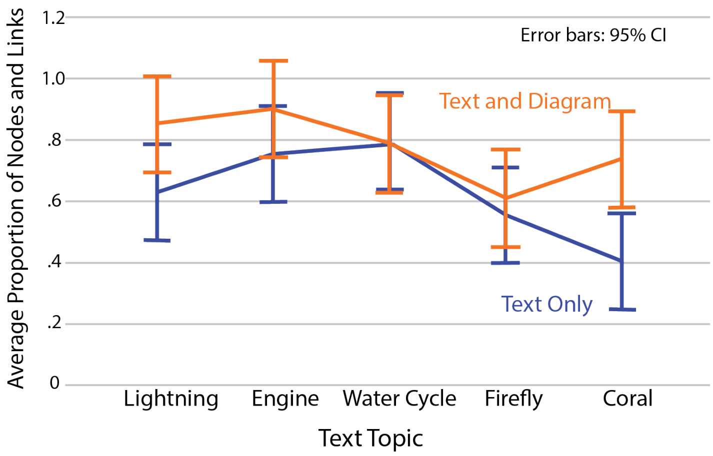
The study was administered in a self-paced Qualtrics survey. After giving consent, one of five texts (selected at random) was presented with or without (determined at random) its corresponding diagram. The instructions were to read the text and "try to understand how <*the science model*> works." They took as much time as desired, and then were asked to write "your own explanation of how it works" from memory. Finally, they took the multiple-choice test and answered demographic questions. Participants completed the experiment in under 10 m on average.

Results

Each written explanation was coded for the presence of causal nodes and links, and two independent coders reached a substantial level of agreement (86.4%), Cohen's *kappa* = .661, $p < .001$ (Landis & Koch, 1977). Between-subjects factorial ANOVAs (SPSS version 27) compared explanations after reading the five texts (*Engines, Coral, Lightning, Fireflies,* and *Rain*) with and without its diagram, with 12 participants per condition. The average reading and explanation times were similar with and without the diagram, and multiple-choice tests revealed no differences and no interaction with Texts, (all Fs < 1.5). Those seeing a diagram wrote longer explanations (as a proportion of presented text length) (M = .405, SE=.025; Text Only M=.335; SE=.025), $F(1, 110) = 3.798$, $p < .05$, η2 =.033. Learners' explanations averaged just 354.5 characters (SD = 183.1), less than half as long as the text they read (M = 958.1, SD = 0.204).

More importantly, the explanations differed in quality when a diagram was presented (Figure 3). The *Diagram* group produced explanations with a higher proportion of correct nodes and links (M = .744; SE = .035; M = .627; SE = .035), $F(1, 110) = 8.701$, $p < .01$, η2 = .073, for four of five texts, with a 12% average improvement and a significant linear contrast with Topic difficulty, $F(4, 110) = 4.567$, $p < .01$, η2 = 14.2.

Figure 3
Explanation Quality by Topic and Text Presentation



To investigate qualitative differences in the qualities of explanations, we created summary diagrams for each text to display how many people (out of 12 in each group) produced each node and link in their explanations. By subtracting the *Text Only* group count from the *Diagram* group count, the *differences* (darker indicates bigger) in explanations (shown in Figure 1) show gains (in blue) and losses (in orange) with presented diagrams.

Across these summary figures, qualitative differences in the causal models with diagrams are evident:

- *Beginning Links: Text Only* learners recreated the start of causal chains in their explanations.
- *Intermediate Links: Diagram* learners reported more intermediate links for all five topics.
- *Ending Links:* Most learners focused on the end of the causal models in their explanations.
- *Complete Models: Diagram* learners offered more complete causal models in their explanations.

These qualities suggest different causal model patterns (e.g., common-cause, common-effect, causal) – pose different challenges for learners. However, across texts, providing diagrams resulted in more learners creating more holistic and complete causal explanations.

Discussion

This study tested learners' explanations of science phenomena to explore how causal diagrams help learners understand science texts (McCrudden et al., 2007; McCrudden et al., 2009; Bobek & Tversky, 2016; Fiorella & Mayer, 2013; Guerrero & Wiley, 2021; Guo et al., 2020). Generating explanations requires a holistic understanding of the *pattern* of causal relationships in a scientific phenomenon. Learners who saw a causal pattern diagram produced more complete causal chains with more intermediate links. The findings suggest diagrams provide more explicit guidance on *what* to learn – general patterns of causal relationships – and improve understanding of complex science models. Multiple-choice tests fail to identify these differences with provided diagrams, suggesting factual tests may underestimate qualitative differences in science understanding.

Unlike classroom learners, our adult sample had little stake in learning outcomes, and we did not measure other outcomes such as vocabulary. Diagrams may matter even more when learners assume a need to remember (Thiede et al., 2010). Seeing or creating a causal diagram during learning may highlight causal relationships in science texts (Zwaan, 1994), resulting in more holistic models supporting explanation (McCrudden et al., 2007; 2009). Other strategies may also support causal learning in science domains (Poliquin & Schraw, 2013; Subramonyam et al., 2019). To make science more accessible to all learners, expanding paradigms for building holistic causal models in science may better prepare citizen scientists to grasp phenomena such as climate change.

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