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Learning science concepts through prompts to consider alternative possible worlds

Angela Nyhout [a,*], Patricia A. Ganea [b]

[a] School of Psychology, University of Kent, Canterbury, Kent CT2 7NP, UK
[b] Applied Psychology & Human Development, University of Toronto, Toronto, Ontario M5S 1V6, Canada

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ABSTRACT

We investigated whether prompting children to think counterfactually when learning a complex science concept (planetary habitability) would promote their learning and transfer. In Study 1, children (*N* = 102 6- and 7-year-olds) were either prompted to think counterfactually about Earth (e.g., whether it is closer to or farther from the sun) or prompted to think about examples of different planets (Venus and Neptune) during an illustrated tutorial. A control group did not receive the tutorial. Children in the counterfactual and examples groups showed better comprehension and transfer of the concept than those in the control group. Moreover, children who were prompted to think counterfactually showed some evidence of better transfer to a novel planetary system than those who were prompted to think about different examples. In Study 2, we investigated the nature of the counterfactual benefit observed in Study 1. Children (*N* = 70 6- and 7-year-olds) received a tutorial featuring a novel (imaginary) planet and were either prompted to think counterfactually about the planet or prompted to think about examples of additional novel planets. Performance was equivalent across conditions and was better than performance in the control condition on all measures. The results suggest that prompts to think about alternative possibilities—both in the form of counterfactuals and in the form of alternative possible worlds—are a promising pedagogical tool for promoting abstract learning of complex science concepts.

* Corresponding author.
E-mail address: a.nyhout@kent.ac.uk (A. Nyhout).

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Introduction

A reliable indicator of one's understanding of a science concept is the ability to transfer what one has learned to exemplars and contexts with low surface similarity—a task known to be challenging for children (Bransford, Brown, & Cocking, 2000; Brown, Kane, & Long, 1989; Gentner, 1989). A significant challenge for researchers and educators, therefore, is to identify methods to support children's ability to transfer newly acquired concepts to novel contexts. In the current studies, we proposed and tested one such method, *guided counterfactual reasoning,* which could be easily integrated into guided learning contexts, including classrooms and museums.

One common approach to promoting transfer involves presenting learners with multiple exemplars of a concept, phenomenon, or solution (Minervino, Olguin, & Trench, 2017). Compared with cases where the learner has seen only a single example, presenting two or more exemplars allows the learner to identify abstract features or principles that generalize across contexts. According to structure mapping theory, learners place exemplars in structural alignment by comparing across them, which highlights their commonalities and differences (Gentner, 1983; Gentner & Markman, 1997). Research with both children and adults across several domains of learning provides support for this approach. For instance, comparison across exemplars facilitates adults' transfer of problem solutions (Gentner, Loewenstein, & Thompson, 2003; Gick & Holyoak, 1983; Kurtz & Loewenstein, 2007) as well as children's word learning and category learning (Gentner & Namy, 1999; Namy & Gentner, 2002) and learning of complex science concepts (Brown & Kane, 1988; Ganea, Ma, & DeLoache, 2011; Strouse & Ganea, 2021).

However, in certain cases, using different examples might not be optimal or feasible. Imagine that one wants to teach a learner about migration paths in animals by presenting different examples. Learning about migration in monarch butterflies and humpback whales, for instance, may present considerable challenges given the number of variables that distinguish the two species (e.g., size, habitat, diet, mating patterns, lifespan). According to structure mapping theory, in the case of multiple examples, those that share surface similarities are more easily comparable and as a result are easier to align on certain abstract dimensions (Gelman, Raman, & Gentner, 2009; Gentner & Gunn, 2001). For certain concepts, we may also lack similar examples to promote abstract learning and transfer. Imagine, as in the current study, that one wants to teach a child about planetary habitability. Because we lack detailed knowledge about planets beyond our solar system, there are limited examples one can provide of habitable planets (i.e., Earth and potentially Mars). How, then, might one promote children's abstract learning and transfer of science concepts in the absence of many viable examples? In the current studies, we proposed that guiding children to think counterfactually about a particular exemplar may promote these abilities.

When reasoning counterfactually, an individual constructs an alternate representation to reality by considering possible outcomes following the manipulation of a variable. Researchers have pointed to the overlap between the development of counterfactual reasoning and both causal reasoning (Buchsbaum, Bridgers, Skolnick Weisberg, & Gopnik, 2012; Gopnik et al., 2004; Harris, German, & Mills, 1996; Weisberg & Gopnik, 2013) and scientific reasoning (Rafetseder & Perner, 2014; Wenzlhuemer, 2009), and some have argued that the imagined manipulations carried out during counterfactual reasoning are akin to actual manipulations of variables carried out during scientific experimentation (Gopnik, 2009; Nyhout & Ganea, 2021; Pearl, 2000; Walker & Gopnik, 2013). The objective of scientific experimentation is, of course, to yield generalizable knowledge about the world by intervening on a variable to uncover its effects. The *imagined interventions* carried out during counterfactual thinking may similarly promote generalization by allowing the reasoner to compare two models of the world: one of the world as it is and one of the world as it *could be* given a specific change. These two models may be thought of as a control condition and a treatment condition, respectively. As with experiments conducted in the real world, these imagined experiments may lead to generalizable knowledge about the role of causal variables that goes beyond the specific example (or sample) examined.

Imagined interventions by way of counterfactuals may be particularly useful when learning about concepts where it is difficult to conduct real-life experiments or even make firsthand observations. Despite this link, no previous work, to our knowledge, has looked at the relationship between counterfactual reasoning and children's generalization of scientific concepts. Crucially, counterfactuals may be used to glean new knowledge and understanding in the absence of additional examples or data. One can take what one already knows (e.g., about Earth) and imagine changes that yield alternate models or representations of the same example from which one can draw conclusions.

An alternate proposal for a potential benefit of counterfactuals on learning and transfer is more general. Specifically, researchers have proposed that thinking counterfactually induces a counterfactual mindset that is more open to alternative possibilities (Galinsky & Moskowitz, 2000; Hirt & Markman, 1995). Thinking about alternative possibilities by way of counterfactuals and multiple explanations has been found to lead to a broad range of benefits, including debiasing predictions and hypothesis testing (Galinsky & Moskowitz, 2000; Hirt & Markman, 1995; Nyhout, Iannuzziello, Walker, & Ganea, 2019), increasing attention to anomalous evidence (Engle & Walker, 2021), and decreasing functional fixedness (Galinsky & Moskowitz, 2000). Together, these findings suggest that counterfactuals may lead learners to approach new tasks flexibly, shedding common biases and shortcomings, by encouraging the consideration of alternative possibilities.

In the current studies, we investigated the impact of guided counterfactual reasoning on children's learning in the domain of *planetary habitability,* a concept that involves a complex causal chain (Fig. 1) and one that children can neither readily observe nor intervene in. We measured both children's comprehension (i.e., their ability to explain the concept in relation to the content already provided) and children's transfer (i.e., their ability to extend the concept to a novel planetary system). Extensive prior work demonstrates that children's learning is often tied to the specific content that has been trained, and abstract transfer or generalization can be a challenging task for learners (e.g., Brown et al., 1989; Gentner, 1989; Marcus, Haden, & Uttal, 2018; Strouse, Nyhout, & Ganea, 2018).

In Study 1, children were given a short illustrated tutorial on planetary habitability and were then guided to think counterfactually about Earth or to think about examples of different planets. A third group of children were not exposed to the learning content or guided prompts and served as a control group. Given previous work showing that presenting multiple exemplars fosters learning, we expected that children who were presented with exemplars of different planets (e.g., Earth, Venus, Neptune) would show better comprehension and transfer compared with those in the control group. However, we were primarily interested in testing the efficacy of the novel approach of guided counterfactual thinking.

We expected that children in both the guided counterfactuals and guided examples conditions would show better comprehension and transfer than those in the control group, but we proposed that the mechanisms underlying the proposed benefits of examples and counterfactuals are different. In the case of multiple examples, the learner aligns models of the exemplars (e.g., Earth, Neptune) and identifies their commonalities and differences. These models may vary from one another on a number of dimensions (e.g., distance, size, color). To make use of these examples, the learner must focus on the variables that are most relevant to the concept at hand and ignore extraneous ones (e.g., color).

In the case of counterfactuals, the learner takes a single model (e.g., Earth) and introduces changes to it—reasoning through the consequences of these changes. Comparing between the model of reality and its alternative may allow the learner to draw generalizable conclusions. Suppose, as in the current study, one wants the learner to grasp the abstract principle that distance of a planet from its star matters for habitability. By considering two models of Earth: one in its actual position and one closer to the sun, the child may reinforce the lesson that "distance matters" by seeing how Earth in a nearer or farther position would render it uninhabitable.

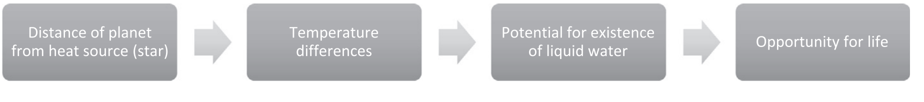

Fig. 1. A causal chain of planetary habitability based on the distance of a planet from its star.

We tested 6- and 7-year-olds for two reasons. First, children in this age range in Ontario, Canada have learned many of the isolated facts underlying this concept (e.g., the sun is a source of heat; living things need water to survive) but have not yet learned the concept itself (Ontario Ministry of Education, 2007), and therefore the instructed content was novel but within reach for most children. Second, children in this age range are capable of engaging in counterfactual reasoning about various types of content (e.g., Beck & Riggs, 2014; McCormack, Ho, Gribben, O'Connor, & Hoerl, 2018; Nyhout & Ganea, 2019a, 2019b).

Study 1

Method

In Study 1, we introduced children to a critical variable influencing planetary habitability: distance of a planet from its star. Children were exposed to the concept in an illustrated tutorial, during which they were guided either to think counterfactually about Earth or to think factually about examples of other planets (Venus and Neptune). A control group of children did not receive exposure to the concept.

Participants

Participants were 101 children aged 6 and 7 years (M = 7.02 years, SD = 0.47, range = 6.03–7.98; 48 girls). Participants were randomly assigned to a *counterfactual* condition (n = 33), an *examples* condition (n = 32), or a *control* condition (n = 36). All participants were tested between April 2016 and March 2017 in a semi-private area of a science museum (n = 39) or in a university laboratory (n = 62). For inclusion in the study, children needed to be exposed to English at least 50% of the time, as assessed by parental report. An additional 5 children were tested, but their data were excluded due to failing pretest (n = 2), parental interference (n = 1), insufficient exposure to English (n = 1), or loss of video (n = 1).

Parents reported the participating children's ethnicity as follows: White (38%), mixed ethnicity (10%), Chinese (8%), South Asian (5%), Southeast Asian (3%), Latin American (2%), West Asian (2%), Japanese (2%), and Jewish (1%). Parents reported their education level as undergraduate degree (27%), graduate or professional degree (25%), community college diploma (10%), high school (6%), or some high school (5%). About a third of parents did not provide demographic information.

Design

Stimuli and test questions are presented in full in the Appendixes A and B, respectively. We created two versions of the tutorial to teach children the concept of planetary habitability. An illustrator created visuals for the purpose of the study. Each picture was displayed on a PowerPoint slide with a black background and accompanying text below the picture.

The first 7 slides of the tutorial were identical. On the 8th through 15th slides of the *counterfactual* version, children were prompted to imagine that the Earth was closer to and farther from the sun. On the corresponding slides of the *examples* version, children were prompted to imagine life on Venus and Neptune. The wording and images were matched as closely as possible across the two versions of the tutorial.

Procedure

The experimenter first asked children 4 *pretest questions* to ensure that they had prerequisite knowledge important to understanding the tutorial. The questions, listed in Appendix B, were focused on children's understanding of what happens to water when cooled or heated and what happens to plants and animals if they do not have water. When asked what happens to water when it is heated, several children responded that it boils. In these cases, the experimenter asked children, "But do you know what it turns into?" and the following answers were accepted: steam, smoke, (water) vapor, a gas, and evaporates. The concepts covered in the pretest questions had been introduced in children's classrooms based on our review of curriculum documents for the tested age range. Children needed to answer 3 of 4 questions correctly for inclusion in the study. Only 2 children did not meet this threshold, and therefore their data were excluded from the study. In cases where children did not answer correctly, the experimenter provided the correct answer.

Next, the experimenter opened the laptop and introduced the tutorial for children in the counterfactual and examples conditions. The experimenter read the text aloud to children on each page before advancing to the next page. Children in the control condition proceeded directly from answering the pretest questions to answering comprehension questions.

The posttest phase included both *comprehension questions* about Earth's solar system to test children's learning from the tutorial and *transfer questions* about a novel (pretend) planetary system. All questions are listed in Appendix B, and sample questions and responses are presented in Table 1. The experimenter first asked children 3 comprehension questions while an image of Earth's solar system was displayed on the screen to examine their learning of the concept of planetary habitability as it relates to Earth and our solar system (e.g., "Why is Earth a planet that plants and animals can live on?"). She then asked children 7 transfer questions while an image of the novel planetary system was displayed on the screen (e.g., "Which planet might have plants and animals living on it? Why?"). The novel planetary system was displayed right to left, with the star on the right to try to minimize any likelihood that children would think this was a depiction of Earth's solar system given that depictions of our own solar system are usually left to right. The experimenter first asked 4 closed-ended questions, then said "I'm going to tell you the names of some of these planets," and proceeded to name three of the planets and asked participants why each of the planets was or was not habitable.

For all posttest questions, each response was scored for the mention of the following four units that correspond to the causal chain outlined in Fig. 1: distance of planet from sun/star, temperature differences, potential for existence of liquid water, and opportunity for life. We did not expect children to mention each unit in response to every question because doing so may seem repetitive, and therefore we did not expect children to perform at ceiling. Children received a maximum score of 4 on open-ended questions and a score up to 5 on closed-ended questions. Closed-ended questions included an extra point for children's selection of an appropriate planet (e.g., selecting the planet closest to the star as the hottest planet) in addition to the explanation they offered.

All responses were recorded live to the best of the experimenter's ability and were later transcribed fully by the experimenter from a video of each session and then coded. A second individual watched all videos to check for accuracy of transcription. A third individual coded a third of the transcripts. Coding agreement was 97%. All disagreements were resolved through discussion between the two coders.

Results and discussion

Children's pretest performance did not differ across the three conditions (p >.957). To analyze children's performance on comprehension and open- and closed-ended transfer questions, with condition, exact age, and pretest score as predictors and score as the outcome variable, we conducted three separate ordinal logistic regression analyses for each of the dependent measures because the coding scheme and range of scores were slightly different. Each model included condition as a predictor and exact age and pretest score as covariates.

The model including comprehension score as the outcome variable was significant, $\chi^2(4) = 25.86$, p <.001. Both condition, $\chi^2(2) = 16.47$, p <.001, and pretest score, $\chi^2(1) = 10.46$, p =.001, were significant predictors, but age was not a significant predictor (p =.462). Both versions of the tutorial conferred a benefit for children's comprehension of the core concept relative to the control condition (see Table 1 for descriptive statistics and Table 2 for inferential statistics). Performance did not differ significantly between the two experimental groups.

The model including closed-ended transfer score as the outcome variable was also significant, $\chi^2(4) = 20.98$, p <.001. Condition was a significant predictor of score, $\chi^2(2) = 17.71$, p <.001, but pretest score, $\chi^2(1) = 3.10$, p =.078, and age, $\chi^2(1) = 0.13$, p =.722, were not significant predictors. Both the counterfactual and examples versions of the tutorial conferred a benefit for children's closed-ended transfer relative to the control condition. Performance between the two experimental conditions did not differ significantly.

Table 1
Mean scores (and standard deviations) on different sets of questions in Studies 1 and 2 grouped by condition.

Question type	Study 1 scores			Study 2 scores		Sample question	Sample response
	Counterfactual–Earth	Examples–Venus/Neptune	Control	Counterfactual: Novel planets	Examples: Novel planets		
Pretest	3.48 (0.83)	3.69 (0.47)	3.64 (0.76)	3.63 (0.49)	3.51 (0.56)	"What happens to water when it gets really, really cold?"	"It freezes or turns into ice."
Comprehension	5.12 (1.80)	5.00 (1.69)	3.58 (1.80)	5.34 (1.66)	5.71 (1.74)	"Why is Earth/Kepler a planet that plants and animals can live on?"	"It is in the middle; it has enough distance from the star and from far away so it can stay hot and cold so it has water so nature can live."
Closed-ended transfer	6.45 (1.80)	6.38 (1.98)	4.44 (2.75)	6.46 (1.65)	6.77 (1.50)	"Which planet or planets might have liquid water on them? Why?"	"This one [middle] because it's not too far or too close from the sun. It's probably not too hot or too cold."
Open-ended transfer	4.73 (1.57)	3.72 (1.11)	3.50 (1.84)	4.31 (1.64)	4.94 (1.43)	"This is Planet Eris. Animals or plants cannot live there. Why can't animals or plants live there?"	"Because it's really far away from the star so I think it would be freezing cold and all water would freeze. So it would not be able to have life or animals."

Note. Sample questions and responses are provided for each question type.

Table 2
Study 1 results of ordinal regression analyses with condition and age as predictors.

	Parameter estimate	*SE*	Wald's χ^2	*p*	Odds ratio	95% Confidence interval
Comprehension questions						
Counterfactual vs. control	1.71	0.45	14.27	<.001	5.54	[2.28, 13.46]
Examples vs. control	1.43	0.45	9.97	.002	4.19	[1.72, 10.19]
Counterfactual vs. examples	0.28	0.46	0.38	.541	1.32	[0.54, 3.23]
Closed-ended transfer questions						
Counterfactual vs. control	1.77	0.46	14.55	<.001	5.85	[2.36, 14.52]
Examples vs. control	1.62	0.46	12.42	<.001	5.08	[2.06, 12.52]
Counterfactual vs. examples	0.14	.045	0.10	.750	1.15	[0.48, 2.78]
Open-ended transfer questions						
Counterfactual vs. control	1.38	0.46	8.90	.003	3.95	[1.60, 9.76]
Examples vs. control	0.19	0.43	0.20	.656	1.21	[0.52, 2.83]
Counterfactual vs. examples	1.18	0.45	6.80	.009	3.26	[1.34, 7.93]

A different pattern of results emerged when looking at performance on open-ended transfer questions. The overall model was significant, $\chi^2(4) = 19.45$, $p = .001$. Both condition, $\chi^2(2) = 10.26$, $p = .006$, and pretest score, $\chi^2(1) = 4.92$, $p = .027$, were significant predictors, whereas age was marginally significant, $\chi^2(1) = 3.72$, $p = .054$. Training with prompts to think counterfactually about Earth was predictive of significantly higher open-ended transfer scores than the examples and control conditions. Surprisingly, performance did not differ significantly between the examples and control conditions on open-ended transfer.

Children in both experimental conditions showed better comprehension of the concept than children in the control condition (who did not receive the instructional content), and the two experimental groups did not differ significantly from one another in their comprehension scores. These results suggest that the tutorial, regardless of the prompts given, was successful in teaching children the target content. Those who did not receive instruction were not able to arrive at the concept on their own by piecing together preexisting underlying knowledge they had of aspects of the causal chain (e.g., distance from a heat source affects temperature, heat causes water to evaporate).

The pattern of performance on transfer questions was more nuanced, such that children in the counterfactual condition outperformed those in the control condition on all measures. Children in the counterfactual condition also outperformed those in the examples condition on open-ended transfer questions but not on closed-ended questions. Those in the examples condition outperformed those in the control condition on closed-ended transfer score but (surprisingly) not on open-ended transfer score. Why might this be the case? The open-ended questions were more challenging and required children to invoke the entire causal chain (Fig. 1) to explain a novel planet's habitability, whereas the closed-ended questions required children to understand only a segment of the causal chain (e.g., "Which planet is the hottest?"). This finding also underscores the difficulty with far transfer; in some cases, children who had received the instruction in the examples condition struggled to transfer the concept at a level that was significantly better than those who had received no instruction. Children's performance in the counterfactual condition, however, suggests that counterfactual prompts may be a helpful tool for meeting the challenges of far transfer. Thus, children in the counterfactual condition appeared to achieve a more complete understanding of the causal chain than those in the other conditions even though the manipulation between conditions was quite subtle. Children in both the examples and counterfactual conditions were provided with the same explanations for the phenomena in the tutorial, and the only difference was the prompts at the end.

There are a few possible explanations for children's better performance in the counterfactual condition relative to the examples condition. First, the counterfactuals may have conferred a benefit because they provided an imagined intervention. Children who were prompted to think counterfactually had the opportunity to mentally intervene on the causal structure in question and therefore may have gained a more generalizable understanding of said structure. This explanation proposes a *specific* benefit of counterfactuals for reasoning about a particular causal structure. A second explanation proposes a more *general* benefit of counterfactuals. The counterfactual prompts invited children to think about an imaginary or possible—but non-actual—world. Reasoning about possible worlds in the form of counterfactuals may have conferred a particular benefit on transfer questions because transfer questions also required children to reason about non-actual worlds, although the planets in the transfer phase were presented to children as though they were real planets far away. Consistent with arguments that thinking counterfactually leads to a more open-minded or flexible mindset (Galinsky & Moskowitz, 2000), counterfactual prompts may encourage learners to flexibly apply their understanding to new contexts by encouraging a focus on more abstract features of the learning content. Finally, the counterfactual prompts may have conferred a benefit simply because they invited children to think about Earth. Reasoning about non-actual premises involving a highly familiar exemplar may have allowed children to draw more accurate inferences compared with reasoning with less familiar exemplars, namely Venus and Neptune.

To investigate these explanations, we conducted a second study in which we introduced children to a novel planetary system during instruction and prompted them either to think counterfactually about a novel habitable planet, Kepler, or to think about examples of three novel planets: Kepler, Gliese, and Moa. In addition to comparing performance across these two new conditions in Study 2, we compared children's performance in Study 2 with performance across the three conditions in Study 1 to gain a better understanding of the relative benefits of the different types of prompts. Specifically, if counterfactuals are beneficial to transfer because of *specific* effects involving imagined interventions on a causal structure, then we should expect better performance in the counterfactual condition involving novel planets compared with the examples condition involving novel planets. If counterfactuals provide a more general benefit by inviting consideration of alternative possible worlds, then we should expect performance to be relatively equal across both new conditions. Finally, if performance in Study 1 was facilitated specifically by consideration of Earth, then we should expect children's performance across both conditions in Study 2 to be poorer than performance in the Study 1 counterfactual condition.

Study 2

Method

Participants

Participants were 70 children aged 6 and 7 years (M = 6.59 years, SD = 0.50; 32 girls). Participants were randomly assigned to the counterfactual condition (n = 35) or the examples condition (n = 35). Participants were tested between January and September 2021 online via Zoom due to the COVID-19 pandemic and were recruited through an existing participant database or through social media. Children needed to be exposed to English language at least 50% of the time for inclusion in the study. An additional 4 children were tested, but their data were excluded due to failing the pretest questions.

Optional demographic information was provided by 51% of participating families. Parents reported participating children's ethnicity as White (23%), mixed ethnicity (20%), South Asian (4.3%), Chinese (1.4%), Jewish (1.4%), or West Asian (1.4%). Information on parental education level was provided by 50% of families. Parents reported their education level as graduate or professional degree (26%), undergraduate degree (20%), or high school (2.3%).

Design and procedure

Stimuli text and test questions are presented in Appendixes A and B, respectively. Visual stimuli were adapted from and similar to the stimuli used in Study 1, but they also included some copyrighted images and therefore are not reproduced here. Children were given the same 4 pretest questions as in Study 1. The experimenter shared her screen and read the instructional content to children while displaying the accompanying images. The wording of the tutorial was the same as in Study 1 but referred to a novel habitable planet called Kepler rather than Earth. Children in the *counterfactual* condition were then prompted to think counterfactually about Kepler being closer to or farther from its star. Children in the *examples* condition were guided to think about examples of two other novel planets, Gliese and Moa, that were too close to or too far from the star to be habitable.

Children were then asked 3 *comprehension questions.* 4 *closed-ended transfer questions,* and 3 *open-ended transfer questions* that mirrored those asked in Study 1. The only difference from Study 1 was that the first comprehension question referred to Kepler instead of Earth. As in Study 1, we did not expect children to achieve the maximum scores. Study sessions were recorded over Zoom and were later transcribed and coded. Coding took place as in Study 1. A second coder, who was blind to condition, coded one third of participants' responses. Coding agreement was 98%. Any disagreements were resolved through discussion between the two coders.

Results and discussion

Children's pretest performance did not differ by condition (p =.419). We again conducted three ordinal logistic regression analyses for each of the dependent measures (comprehension, open-ended transfer, and closed-ended transfer questions) with condition as a predictor, exact age and pretest score as covariates, and score as the outcome variable. Table 1 presents descriptive statistics, and Table 3 presents inferential statistics for condition comparisons in Study 2. Odds ratios provide an index of effect size for each comparison across conditions.

Table 3
Comparison across Studies 1 and 2 of the ordinal regression analyses with condition, age, and pretest scores as predictors.

	Parameter estimate	*SE*	Wald's χ^2	*p*	Odds ratio	95% Confidence interval
Comprehension questions						
CF (S2) vs. Examples (S2)	0.59	0.43	1.85	.174	1.80	[0.75, 2.34]
CF (S2) vs. *Control (S1)*	1.90	0.45	18.02	<.001	6.68	[2.78, 16.06]
Examples (S2) vs. *Control (S1)*	2.49	0.47	28.20	<.001	12.01	[4.80, 30.06]
CF (S2) vs. *CF–Earth (S1)*	0.34	0.46	0.55	.459	1.40	[0.57, 3.42]
CF (S2) vs. *Examples–Venus/Neptune (S1)*	0.49	0.45	1.18	.277	1.64	[0.67, 3.97]
Examples (S2) vs. *CF–Earth (S1)*	0.92	0.47	3.92	.048	2.52	[1.01, 6.28]
Examples (S2) vs. *Examples–Venus/ Neptune (S1)*	1.08	0.46	5.41	.020	2.94	[1.18, 7.29]
Closed-ended transfer questions						
CF (S2) vs. Examples (S2)	0.42	0.43	0.96	.328	1.52	[0.66, 3.53]
CF (S2) vs. *Control (S1)*	1.86	0.46	16.20	<.001	6.44	[2.60, 15.96]
Examples (S2) vs. *Control (S1)*	2.28	0.48	23.10	<.001	9.81	[3.87, 22.88]
CF (S2) vs. *CF–Earth (S1)*	0.20	0.47	0.002	.966	1.02	[0.41, 2.56]
CF (S2) vs. *Examples–Venus/Neptune (S1)*	0.16	0.46	0.12	.732	1.17	[0.48, 2.87]
Examples (S2) vs. *CF–Earth (S1)*	0.44	0.47	0.86	.354	1.55	[0.61, 3.93]
Examples (S2) vs. *Examples–Venus/ Neptune (S1)*	0.58	0.47	1.53	.216	1.78	[0.71, 4.45]
Open-ended transfer questions						
CF (S2) vs. Examples (S2)	0.87	0.43	4.25	.039	2.43	[1.04, 5.63]
CF (S2) vs. *Control (S1)*	1.26	0.46	7.46	.006	3.54	[1.43, 8.77]
Examples (S2) vs. *Control (S1)*	2.15	0.46	21.62	<.001	8.59	[3.47, 21.25]
CF (S2) vs. *CF–Earth (S1)*	0.08	0.47	0.03	.867	1.08	[0.43, 2.73]
CF (S2) vs. *Examples–Venus/Neptune (S1)*	1.05	0.45	5.36	.021	2.86	[1.16, 6.96]
Examples (S2) vs. *CF–Earth (S1)*	0.81	0.46	3.13	.077	2.24	[0.92, 5.48]
Examples (S2) vs. *Examples–Venus/ Neptune (S1)*	1.94	0.45	18.22	<.001	6.93	[2.85, 16.87]

Note. CF, counterfactual. Conditions from Study 1 (S1) are marked in *italic* typeface, and conditions from Study 2 (S2) are marked in roman typeface.

The model predicting comprehension score was not significant, $\chi^2(3) = 5.50$, $p = .138$. Differences in scores were not predicted by condition ($p = .214$), age ($p = .052$), or pretest score ($p = .312$).

The model predicting closed-ended transfer score was similarly nonsignificant, $\chi^2(3) = 4.10$, $p = .215$, with none of the three variables significantly predicting score: condition ($p = .283$), age ($p = .402$), or pretest score ($p = .087$).

In contrast, the model predicting open-ended transfer score was significant, $\chi^2(3) = 11.00$, $p = .012$. Condition was a marginally significant predictor, $\chi^2(1) = 3.82$, $p = .051$, such that exposure to the examples prompts was actually predictive of marginally higher scores than exposure to the counterfactual prompts. Age was a significant predictor of score, $\chi^2(1) = 6.57$, $p = .010$, whereas pretest score was not ($p = .738$).

Comparison of Study 1 and Study 2 conditions

Children's pretest performance did not differ by condition ($p = .552$). Using three ordinal logical regression analyses for each of the dependent measures, we compared children's performance in the counterfactual and examples conditions in Study 2 with children's performance in the control, counterfactual (henceforth counterfactual–Earth), and examples (henceforth examples–Venus/Neptune) conditions from Study 1, and thus each analysis included five groups.

The model with comprehension score as the outcome variable was significant, $\chi^2(6) = 38.61$, $p < .001$. Both condition, $\chi^2(4) = 31.24$, $p < .001$, and pretest score, $\chi^2(1) = 9.56$, $p = .002$, were significant predictors, whereas age was not a significant predictor ($p = .336$). Children's comprehension scores did not differ significantly between the counterfactual and examples conditions in Study 2. Exposure to the tutorial in both conditions in Study 2 was predictive of significantly higher comprehension scores than in the Study 1 control condition. Moreover, exposure to the tutorial with examples prompts in Study 2 was predictive of significantly better comprehension scores than instruction in Study 1 with either examples–Venus/Neptune or counterfactual–Earth prompts.

The model including closed-ended transfer score as the outcome variable was significant, $\chi^2(6) = 32.99$, $p < .001$. Both condition, $\chi^2(2) = 28.49$, $p < .001$, and pretest score, $\chi^2(1) = 5.77$, $p = .016$, were significant predictors of closed-ended transfer score, whereas age was not a significant predictor ($p = .426$). Performance between the counterfactual and examples conditions in Study 2 did not differ significantly. Exposure to the Study 2 tutorial with counterfactual or examples prompts was predictive of significantly higher closed-ended transfer scores than in the Study 1 control condition. Performance in the two conditions in Study 2 did not differ significantly from performance in the two experimental conditions in Study 1.

Finally, a model including open-ended transfer score was also significant, $\chi^2(6) = 35.71$, $p < .001$. Condition, $\chi^2(4) = 28.10$, $p < .001$, age, $\chi^2(1) = 11.04$, $p < .001$, and pretest score, $\chi^2(1) = 4.03$, $p = .045$ all were significant predictors. Exposure to the tutorial with counterfactual and examples prompts was predictive of a higher open-ended transfer score than in the Study 1 control condition. In contrast to the results of Study 1, instruction with examples prompts in Study 2 was predictive of marginally higher scores than instruction with counterfactual prompts. Instruction in the two conditions in Study 2 was predictive of higher open-ended transfer scores than exposure to the examples–Venus/Neptune instruction in Study 1 but not to the counterfactual–Earth instruction in Study 1.

The transfer results differed from those in Study 1. Unlike Study 1, children in the counterfactual condition did not outperform those in the examples condition. In fact, children in the examples condition performed marginally better than children in the counterfactual condition in the current study. Children in both instruction conditions outperformed those in the control condition on transfer questions, indicating that both types of instruction with prompts facilitated transfer.

General discussion

Across two studies, we investigated the effects of different types of learning prompts on children's learning and transfer of the concept of planetary habitability. Children were prompted to think counterfactually about the distance of a habitable planet from its star and to consider the effects of this change on its habitability *or* to consider examples of different planets that varied in their distance from their star. In Study 1, children who were prompted to think counterfactually about Earth's distance from the sun showed better transfer of the target concept than those in the control group. We also found that children in the counterfactual condition outperformed children in the examples condition—who thought about Earth, Venus, and Neptune—on open-ended transfer questions. Given the difficulties that learners show with far transfer (e.g., Bransford et al., 2000), it is noteworthy that children showed success at transferring their knowledge to a novel planetary system compared with those in the control condition. Both the counterfactual and examples groups outperformed children in the control group on the comprehension measure but did not perform significantly differently from one another.

In Study 2, we introduced children to a novel planetary system similar to our own to further investigate the benefits of counterfactual and examples prompts. In this case, children who were prompted to think about counterfactual versions of a novel planet, Kepler, did not perform significantly differently on comprehension and transfer questions than children who were prompted to think about three novel planets. To better understand the effects of different types of learning prompts, we compared performance across the five conditions in the two studies. Children in both Study 2 conditions outperformed those in the Study 1 control condition by an order of magnitude higher than those in the Study 1 experimental conditions. Relative to control group performance, the instruction with prompts in Study 2 was associated with odds ratios from 3.54 to 12.01 compared with odds ratios from 3.26 to 5.85 for instruction with prompts in Study 1. On some measures, children in Study 2 outperformed those in the Study 1 experimental conditions. Specifically, children in the Study 2 examples condition outperformed those in the Study 1 examples–Venus/Neptune and counterfactuals–Earth conditions on comprehension scores, and children in both conditions in Study 2 outperformed those in the examples–Venus/Neptune condition in Study 1 on open-ended transfer.

These findings support the assertion that counterfactuals—and more broadly prompts to consider alternative possibilities—benefit learning and transfer when children encounter complex causal phenomena. The pattern of performance across the two studies also sheds light on the nature of this benefit. Encouraging children to consider alternative possible worlds—whether in the form of counterfactuals or in the form of novel (imaginary) exemplars—appears to facilitate learning and transfer. It is notable that the weakest performance across the four experimental conditions came when children were prompted to think of realistic exemplars (Earth, Venus, and Neptune) with no deviation from reality. This may be because the exemplars they thought about (e.g., Venus, Neptune) lacked surface similarity and varied along several dimensions (e.g., size, color, composition), which could have made it more difficult to compare them and extract the relevant causal structure (Gentner, 1983; Gentner & Markman, 1997). Having children consider familiar examples therefore may present certain barriers for learning and transfer of a concept like planetary habitability compared with having them consider counterfactuals or novel/imaginary exemplars. Rather than it being the case that familiar exemplars attenuate learning and transfer, it may instead be the case that the process of considering different non-actual possibilities leads to benefits. Our findings suggest that by directing attention away from specific exemplars to counterfactual and alternative possible worlds, children gained a more abstract understanding of the causal principles we aimed to teach.

Following Study 1, we considered two main proposals for the benefit of counterfactuals observed on transfer questions. In Study 2, benefits of considering alternative possibilities were observed not just for transfer but also for comprehension. The first proposal was that counterfactuals function as an imagined intervention, allowing learners to mentally intervene on a causal structure to yield generalizable insights. The second proposal was that counterfactuals, as a form of reasoning about alternative possibilities, have more general benefits by promoting a mindset that is open to alternatives. The results of the current studies are more in line with the second proposal and suggest that it was not counterfactuals per se that benefited performance in Study 1. Hirt and Markman (1995) argued that prompting individuals to consider alternatives leads them to adopt a mindset that is generally open to alternative hypotheses. This proposal connects to a wide body of research with both adults and children suggesting that prompts to think of alternatives facilitate reasoning on an array of tasks (Chakravarty, Srivastava, & Patil, 2020; Galinsky & Moskowitz, 2000; Hirt & Markman, 1995; Nyhout & Ganea, 2019a, 2019b). For instance, adults who have been primed to think counterfactually show more divergent thinking and better performance on a hypothesis-testing task (Galinsky &

Moskowitz, 2000). Other work has found that prompting 7- to 10-year-olds to think counterfactually leads to better performance on a control-of-variables experimental design task compared with children given control prompts (Nyhout & Ganea, 2019a). Another study with preschoolers found that counterfactual prompts scaffolded their ability to detect anomalies to an existing hypothesis in a causal learning task (Engle & Walker, 2021). Research with middle schoolers found that children who were asked to think counterfactually subsequently generated more insightful questions (Chakravarty et al., 2020).

The precise mechanisms underlying these effects may be as diverse as the tasks on which they are put to use. For instance, whereas prompts to consider alternatives may debias reasoning on some tasks by encouraging individuals to consider lower-likelihood hypotheses (Engle & Walker, 2021; Walker & Nyhout, 2020), the facilitating effect in the current studies may be better explained by encouraging a focus on abstract features of the problems by drawing attention to alternative possibilities. Future work may investigate the effects of different types of prompts to consider alternatives on different types of reasoning tasks.

Future work should identify the scope of the facilitating effects of prompts to consider alternatives across a variety of scientific domains. On which types of tasks do they facilitate learning and reasoning? How long-lasting are any effects? The manipulation in the current studies was quite subtle, which has also been the case in previous studies investigating the effects of counterfactuals (Galinsky & Moskowitz, 2000; Nyhout & Ganea, 2019a, 2019b). We may expect effect sizes to mirror the extent of the intervention. With more intense, frequent, or prolonged interventions, is there a similar increase in learning? In which cases may prompts to consider alternatives hinder learning? Research with adults indicates that counterfactual alternatives may *bias* performance on reasoning tasks when consideration of alternative possibilities detracts focus from the task at hand (e.g., affirming the consequent on the Wason card selection task; Galinsky & Moskowitz, 2000). Performance may be similarly limited by the nature of the alternative that individuals generate spontaneously. Out of the infinite alternative possibilities that individuals *could* consider, the mind tends to focus on a select few (Byrne, 2005), and this rather narrow focus may limit the scope of any effects of considering alternatives on learning and reasoning.

As a final note, the results of the current studies could contribute to allaying concerns that instruction delivered online is somehow inferior to in-person instruction. Children in Study 2, who learned the content online, performed just as well as, and in some cases better than, children in Study 1, who learned in-person.

Taken together, the results of the current studies and previous studies suggest that counterfactual prompts and prompts to consider alternative possibilities are a promising pedagogical tool that may help to address the challenges of transfer (Bransford et al., 2000). In particular, the current studies introduce novel pedagogical prompts as a tool for the abstract learning of science concepts that may be as useful as (and in some cases more useful than) prompts to consider multiple existing exemplars. They are low cost and can be easily implemented across a range of formal and informal learning settings. Whether used during book reading with a parent at home or in a classroom when learning a new science concept, prompts to consider alternative possibilities may encourage learners to engage with material in novel ways.

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Appendix A

Study 1 stimuli

1

Let's go on a journey through space!

There are many planets and suns in the universe. When you look up into the sky at night, the stars that you see are suns that have planets orbiting around them.

2

Planet Earth is a part of a planetary system with planets that all orbit around the Sun. There are 8 planets in Earth's planetary system.

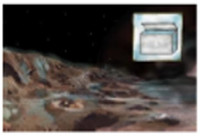
3

But the only planet that has animals and plants living on it is Earth.
Why does Earth have living things on it, and other planets do not?
One reason is because Earth is not too close and not too far away from the Sun. It is just right.

4

Planets that are too close to their Sun are too hot.
The hot planets are so hot that there is no water. If there was ever any water, it would evaporate and all turn into steam right away, like when a kettle is boiling.

5



Planets that are too far from their Sun are too cold.
The cold planets are so cold that there is no water either. If there was ever any water, it would all turn into ice right away, like when you put water in a freezer.

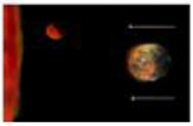
6

Plants and animals need water to live and grow.

7

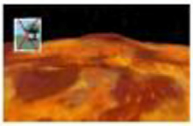
A long, long time ago when Earth was a new planet and the very first living things were born on Earth, they could survive because Earth had liquid water.

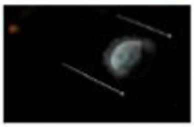
Counterfactual condition:

8 
Now, let's think about if Earth had been very, very close to the Sun. Would it have been hot or cold?

9 
It would have been very hot. Would there have been water to drink?

10 
No! All the water would turn into steam and evaporate right away. Would plants and animals have been able to live on Earth?

11 
Nothing would have been able to live on Earth, because it would be too hot and there would be no liquid water.

12 
Now let's think about if Earth had been very, very far away from the Sun. Would it have been hot or cold?

13 
It would have been very cold. Would there have been water to drink?

14 
No! All the water would freeze right away and stay frozen. Would plants and animals have been able to live on Earth?

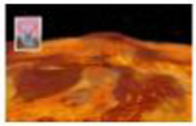
15 
Nothing would have been able to live on Earth, because it would be too cold and there would be no liquid water.

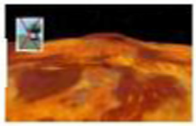
16 
That was a fun journey!

Examples condition:

8 
Now, let's think about a planet called Venus that is very, very close to the Sun. Is it hot or cold?

9 
It is very hot. Is there water to drink?

10 
No! All the water would turn into steam and evaporate right away. Can people and plants and animals live on Venus?

11 
Nothing can live on Venus, because it is too hot and there is no liquid water.

12 
Now, let's think about a planet called Neptune that is very, very far away from the Sun. Is it hot or cold?

13 
It is very cold. Is there water to drink?

14 
No! All the water would freeze right away and stay frozen. Can people and plants and animals live on Neptune?

15 
Nothing can live on Neptune, because it is too cold and there is no liquid water.

16 
That was a fun journey!

Appendix B

Test questions from Studies 1 and 2

Pretest questions

1. What happens to water when it gets really, really hot?
2. What happens to water when it gets really, really cold?
3. What happens to animals if they don't have any water for a long time?
4. What happens to plants if they don't have any water for a long time?

Comprehension questions

1. Why is Earth/Kepler a planet that plants and animals can live on?
2. Can plants and animals live on a planet that is very, very far away from the sun/star? Why/why not?
3. Can plants and animals live on a planet that is very, very close to the sun/star? Why/why not?

Transfer questions

Closed-ended questions

Experimenter says, "Now I'm going to show you some new planets that we haven't seen before.".

1. Which planet is the hottest/coldest? Why?
2. Which planet is the hottest/coldest? Why?
3. Which planet or planets might have liquid water on them? Why?
4. Which planet might have plants and animals living on it? Why?

Open-ended questions

Experimenter says, "I'm going to tell you the names of some of these planets.".

1. This is Planet Moa/Ceres. Animals or plants cannot live there. Why can't animals or plants live there?
2. This is Planet Gliese/Eres. Animals or plants cannot live there. Why can't animals or plants live there?
3. This is Planet Kepler/Varuna. Animals and plants can live there. Why can animals and plants live there?

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