Analogical Reasoning During Hypothesis Generation: The Effects of Object and Domain Similarities on Access and Transfer

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Abstract

In two experiments on analogical hypothesis generation, we factorially manipulated the presence of domain and object similarities between a base situation and a target phenomenon, and assessed their effects on the transfer of the source's explanatory structure before and after an indication to use the base analog as a source for analogical explanations. The absence of any kind of surface similarity led to very low rates of spontaneous transfer. In both experiments, however, either kind of surface similarity sufficed to enhance the spontaneous transfer of the base explanation during the formulation of plausible hypotheses for the target. The transfer advantage of object and domain similarity cannot be attributed to the effect of these variables on post-access processes, since experimental conditions did not differ with regard to the ability to transfer the base explanation upon explicit request. The effect of domain similarity on spontaneous analogical explanation constitutes a relevant finding, especially given the lack of attention received by this dimension of similarity in behavioral studies and computer simulations of analogical retrieval.

Keywords: analogy; retrieval; transfer; hypothesis generation

Introduction

In everyday situations and educational contexts, people are constantly faced with unknown phenomena for which they lack a causal explanation. In the process of formulating plausible hypotheses, a potentially useful heuristic consists in retrieving an analogous case whose explanation is known (base analog), and adapting its explanatory structure to the particulars of the current situation (target analog).

The use of analogies in hypothesis generation has been investigated in retrospective studies of scientific discoveries (Gentner, et al., 1997; Nersessian, 1992), observational studies of scientists and engineers (Dunbar, 1995; Chan et al., 2012), and think-aloud interviews with science experts (Clement, 1988; 2008). Although this research has clarified the role of analogies in expert reasoning, little is known about how novices retrieve and use analogous cases for generating hypotheses.

The available evidence on how non-experts spontaneously retrieve and use analogous cases comes mostly from studies of problem-solving. In a typical experimental procedure, participants begin by studying a problem and its solution. After a contextual separation, they are presented with an unsolved situation whose individual elements are organized by a system of relations and roles that is similar to that of the learned situation (*structural similarity*). One of the most robust findings within the problem-solving literature is that structural similarity alone does not suffice for analogical retrieval to occur. When the individual objects and first-order relations of the base analog do not match those of the target, as it is normally the case when problems belong to different domains of knowledge, a structurally equivalent base situation is unlikely to be retrieved (Gick & Holyoak, 1980; Holyoak & Koh, 1987; Keane, 1987; Kurtz & Loewenstein, 2007; Minervino, et al., 2017). Thus, although the inferential power of a base analog is fundamentally based on its shared relational structure with the target, memory retrieval seems to be largely determined by matches in semantic aspects that are irrelevant to the problem's solution (Gentner et al., 1993).

Consistent with the available empirical evidence, computer models of analogical retrieval like MAC/FAC (Forbus, et al., 1994) or LISA (Hummel & Holyoak, 1997) converge in regarding surface similarity as the main contributor to retrieval. Once superficially similar situations are retrieved, a more costly processing of structural similarity favors candidate situations that also maintain structural similarities with the target.

Dominant models of analogical retrieval restrict the computation of surface similarity to the semantic similarities between objects and first-order relations of the base and the target analogs. However, some authors have argued that more precise distinctions of surface similarity are needed (Ross, 1987, 1989; Ripoll, 1998). Ross (1987) distinguished between similarity of objects and similarity of cover stories within which the structural features of a given problem are embedded.

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He demonstrated that while both dimensions affect access, only object similarities influence how the solution of a retrieved problem is applied to the target. Ripoll (1998) argued that the probability of retrieving a suitable analog would be too low if surface similarity between objects were the only cue that drives the initial phase of the search process. Instead, he hypothesized that more abstract representations may serve to constrain surface similarities between objects by delimiting a search space in long-term memory (LTM) from which the extraction of useful information is carried out (the "search-area" effect). One of such abstract representations is the *domain* of a given situation, which describes a general context or setting. After having identified the domain to which a situation belongs (e.g., chemistry, military, sports), the search process can be focused on that particular subset of LTM. Consistent with this hypothesis, Ripoll (1998, Experiment 1) showed that the simultaneous presence of these two kinds of surface similarity was a necessary precondition for analogical retrieval. The main objective of the present research consisted in assessing the differential effect of these two kinds of surface similarity on the cognitive processes that take place during analogical hypothesis-generation, an educationally-relevant activity that has seldom been investigated among novices.

Experiment 1

Method

Participants and design. A total of 148 undergraduate students (Age $M = 26$; $SD = 8.11$; 81 women) from university majors unrelated to natural sciences voluntarily participated in the study. They were randomly assigned to four experimental conditions arising from the crossing of two levels of objects similarity (high vs. low) and two levels of domain similarity (high vs. low) between a base situation and an analogous counterintuitive phenomenon whose underlying causal explanation was not known by participants.

Materials. In all conditions, base and target situations were characterized by mixtures with non-additive volumes (see Table 1). The target analog described a decontextualized situation clearly ascribed to the chemistry domain, wherein the mixture of two liquid substances (alcohol and acetone) surprisingly yields a total volume that is less than the sum of their individual components. While the base analogs with high domain similarity involved contextual elements that made the situation easily recognizable within the chemistry domain (e.g., researchers, experimental trials, molecules, etc.) the base analogs without domain similarity had story lines intended to evoke the domains of *maintenance* and/or *management* (e.g., swimming pools, maintenance, low price, bulk unload, etc.). With regard to the object similarity manipulation, while the base analogs with similar objects also involved liquid substances, the base analogs with dissimilar objects involved solid substances. The base stories had a length of between 100 and 130 words.

Table 1: Base and target analogs, Experiment 1.

Similar domain base analogs *with* and [without] object similarities: A group of young researchers were examining the effects of mixing diverse *liquids* [salts]. During one of the experiments, the researchers decided to use *400 ml of water* [400 cm³ of copper sulfate] and *600 ml of benzene* [600 cm³ of calcium fluoride]. After carefully measuring the initial amounts of both *liquids* [salts], they combined them in the same glass container, trying not to spill any *drop* [grain] out of the glass. To their surprise, the amount of the resulting mixture was not *1000 ml* [1000 cm³] as they expected, but only *950 ml* [950 cm³]. Then they understood the cause of this contraction: since *water molecules* [grains of copper sulfate] are much smaller than *benzene molecules* [calcium fluoride grains], when mixed with each other the *water molecules* [grains of copper sulfate] tended to fill the empty spaces that remained between the *larger molecules of benzene* [grains of calcium fluoride].

Cross-domain base analogs *with* and [without] object similarities: A club received an offer to buy *1000 liters of liquid products* [4 m³ of stone bricks] needed to maintain their *pools* [tennis courts] during the season. The reason for the low price was that the *liquids* [stones] were not *bottled* [bagged] but unloaded in bulk. As there were no containers to store it, the person in charge of maintaining the *pools* [courts] decided to deposit it in a *1000-liter* [4 m³] children's pool that was in disuse. One *tank truck* [warehouse] provided *400 liters of chlorine* [3 m³ of pebbles], and another provided *600 liters of water* [1 m³ of stones]. The trucks unloaded the *liquids* [stones], without letting any *drop* [stone] fall out of the pool. To everyone's surprise, the *1000-liters* [4 m³] of the pool were not filled, but only *950 liters* [3.5 m³]. Then they understood the cause of this contraction: since *chlorine molecules* [pebbles] are much smaller than *water molecules* [stones], when mixed with each other the *chlorine molecules* [small pebbles] tended to fill the empty spaces that remained between the larger *molecules of water* [stones].

Target Analog. After combining 1 liter of alcohol and 1 liter of acetone, the resulting volume is not equal to 2 L, but to just 1.9 liters. Why do you think this could have happened?

Note. The text in italics was included in the similar objects conditions. Text between brackets corresponds to the dissimilar objects conditions.

Procedure. The experiment was administered online due to the pandemic restrictions (https://www.cognition.run/). After an informed consent, the first phase of the experiment was presented to participants as a reading comprehension activity. While the first and last stories served as distractors, the second situation (base analog) was analogous to the critical phenomenon to be presented during the transfer phase. On the screen following each story, three free-response questions were asked about each situation. With regards to the base analog, participants were asked about (1) the purpose of the mixing, (2) the effects of the mixing, and (3) the explanation for said phenomenon. The questions were included to enforce a careful encoding of the stories in LTM.

After the first phase, participants completed a short Raven test (Arthur & Day, 1994) intended to impose a contextual separation between the encoding and the transfer phases. The task had no set-time limit, but participants required approximately 15 min to complete it.

The transfer phase was presented as a hypothesis generation task. Participants were told that they would be presented with scientific phenomena about which they would have to generate plausible causal explanations, without consideration of whether or not the generated hypotheses were scientifically correct. After presenting an example of a counterintuitive phenomenon followed by two defensible explanations, participants read two new scientific phenomena about which they had to generate their own hypotheses. While the first phenomenon served as a distractor, the second phenomenon (target analog) was analogous to the second situation of the preceding phase.

In order to explore the extent to which analogical transfer can take place in the absence of a conscious activation of the source situation (see e.g., Day & Gentner, 2007; Day & Goldstone, 2011; Schunn & Dunbar, 1996), a post-task questionnaire directly queried participants about whether or not any of the stories read during the text comprehension activity had come to mind, even if briefly, while they were generating explanatory hypotheses for the second phenomenon. Participants who answered "yes" were asked to indicate which story (or stories) had come to mind.

Previous studies (e.g., Clement, 1993) have revealed that students can sometimes understand thematically distant analogies but nevertheless refrain from considering them as plausible sources of explanations for a target phenomenon. Conceived as a materials check, a further item of the post-task questionnaire asked participants to rate on a 5-point Likert scale (1 = not reasonable at all, 5 = very reasonable) the extent to which they judged it appropriate to explain the target phenomenon on the basis of the explanation provided for the second situation of the reading comprehension activity, justifying the reasons for their ratings.

Finally, participants were told that the second story of the reading comprehension activity was in fact analogous to the second phenomenon for which they had to generate plausible explanations, and were explicitly asked to explain this second phenomenon by analogy to the base situation. This last measure was intended to assess whether eventual differences in spontaneous transfer were due to differential difficulties across conditions with regard to post-access processes involved in applying a retrieved source to the target phenomenon.

Data analysis. Two independent raters blind to the objectives of the study classified participants' hypotheses as involving analogical transfer whenever they attributed the volume contraction to either (a) a packing/ compaction process or (b) the different size of molecules, atoms or particles.

Results. Four participants were excluded from the analysis for not having completed all sections of the experiment.

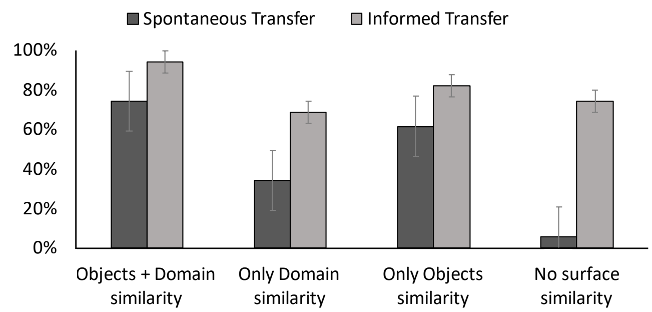

Figure 1: Spontaneous and Informed transfer rates, Experiment 1.

Spontaneous Transfer. The percentages of participants who spontaneously transferred the base situation while generating hypotheses for the target were of 74% when both similarities were present, of 34% when there was only domain similarity, of 61% when there was only object similarity, and of 5% in the lack of any kind of surface similarity (see Figure 1). A logistic regression model revealed positive effects of object similarity (*ß* Estimate = 3.27, *SD* = 0.79, Wald *Z* = 4.09, *p* = .000), and domain similarity (*ß* Estimate = 2.15, *SD* = 0.81, Wald *Z* = 2.65, *p* = .007) on the spontaneous transfer of the base explanation. The interaction between both variables was not significant (*ß* Estimate = -1.56, *SD* = 0.95, Wald *Z* = -1.63, *p* = .102). As compared to the condition lacking both kinds of similarity, the addition of object similarity exerted a stronger effect than the addition of domain similarity on the spontaneous transfer of the base explanatory structure (*ß* Estimate = 1.12, *SD* = 0.48, Wald *Z* = 2.31, *p* = .02). Among participants who generated the intended solution to the target problem, only one reported not having retrieved the base analogue while attempting to explain the target.

Informed Transfer. The percentages of participants who could successfully transfer the base explanation upon explicit request were of 94% when both similarities were present, of 68% when there was only domain similarity, of 82% when there was only object similarity, and of 74% in the lack of any kind of surface similarity (see Figure 1). A logistic regression model revealed that neither object similarity (*ß* Estimate = 0.45, *SD* = 0.56, Wald *Z* = 0.80, *p* = .41), nor domain similarity (*ß* Estimate = -0.28, *SD* = 0.53, Wald *Z* = -0.52, *p* = .59) were predictors of informed transfer. The interaction between both kinds of similarities was not significant (*ß* Estimate = 1.12, *SD* = 0.90, Wald *Z* = 1.24, *p* = .21).

Plausibility. The scores received by the base analog as a reasonable foundation for explaining the target phenomenon were of 3.3 (object and domain similarities), 3.1 (domain similarity), 3.7 (object similarity), and 3.5 (neither kind of similarity). As the differences between the groups were not significant, the inferior transfer performance obtained in conditions lacking object and/or domain similarity cannot be attributed to a diminished plausibility of the base analogs as sources of explanatory structure for the target situation.

Discussion. When both object and domain similarities were lacking, participants massively failed to transfer the explanatory structure from the base situation to the target phenomenon. However, either object or domain similarities alone sufficed to boost retrieval considerably. The self-standing effect of domain similarity constitutes a relevant finding, especially given the lack of attention received by this dimension of surface similarity in behavioral studies and computer simulations of analogical retrieval.

The fact that virtually all participants who generated the intended solution reported having been reminded of the base analog suggests that, at least during early exposure to instances of a given explanatory mechanism, participants are unlikely to extrapolate the learned explanation without also retrieving the specific case in which such explanation was embedded.

The absence of an interaction between object and domain similarity was somewhat surprising, especially in the context of Ripoll´s (1998) claim that object similarities are ill-suited for adequately constraining memory search in the lack of the concurrent presence of domain similarity. One possibility behind this non-significant interaction might relate to the construction of our experimental materials. Despite our efforts to construct a base situation whose story line was as removed as possible from the chemistry domain (swimming-pool management), it seems plausible that certain entities included in its causal explanation (e.g., *molecules*) are so standardly associated with the chemical domain that their mere presence could have caused the situation to be indexed in LTM as belonging to said domain. Hence, it is possible that for some participants in the object similarity condition, the domain of the target situation (chemistry) might have served as a cue to the base scenario.

To reassess Ripoll´s (1998) interaction hypothesis while controlling for this possibility, we carried out a follow-up experiment in which the order of the base and target analogs was reversed (i.e., the target phenomenon was converted into a single base analog for all conditions by way of adding a causal explanation, and the base situations were converted into four different target phenomena by means of removing their explanations). This way, while the base analog was intended to uniformly elicit the chemistry domain across conditions, the removal of an explanation from the four stories now serving as targets ensured that none of the "swimming pool" scenarios would elicit the chemistry domain by themselves.

Beyond eliminating a potential confounding between object and domain similarity, we reasoned that the intended base-target inversion could also alleviate some additional difficulties that those participants who received analogs without similar objects might have faced during the post-access subprocesses of mapping, inference, and adaptation. Even though in Experiment 1 participants in the "dissimilar objects" conditions were not outperformed by those in the "similar objects" condition when explicitly asked to transfer the base explanation to the target, it could conceivably be the case that in the absence of such indication, a proportion of participants who had spontaneously retrieved the solid mixtures situations during the first encounter with the target might have failed to carry-out the necessary reconceptualization of the liquids involved in the target mixture as composed of discrete units whose size differs from one liquid to the other. As shown by a large body of science education research (e.g., Garcia Franco & Taber, 2009; Löfgren & Helldén, 2009; Valnides, 2000), students at all educational levels often fail to spontaneously use their knowledge about the corpuscular nature of matter when explaining everyday situations. With the base-target inversion implemented in Experiment 2, those conditions with dissimilar objects will now receive a target in which the corpuscular nature of the combined elements is already apparent (*grains*/*stones*), thus facilitating post-access processes of mapping, inference and adaptation. Therefore, they will become more similar to those of the complementary conditions, in which the corpuscular nature of the elements involved in the liquid mixtures, although not explicit, can be directly inferred from the explanation that corresponds to the retrieved base analog, which also involved liquid mixtures. This way, all conditions could be considered more equivalent than those of Experiment 1 in terms of post-access difficulties.

Experiment 2

Method

Participants. A total of 140 undergraduate students (Age M = 24, SD = 5.76, 91 Female) volunteered to participate in the study and were randomly assigned to the same four experimental conditions as in Experiment 1.

Materials. In converting the target phenomenon of Experiment 1 into the base situation, the original requirement to explain the volume contraction phenomenon was replaced by the following explanation: "*since alcohol molecules are much smaller than the acetone molecules, when mixing with each other it happened that the alcohol molecules tended to fit into the empty spaces between the relatively larger acetone molecules*". Conversely, adapting the base stories of Experiment 1 to function as targets involved replacing the original explanations of the critical phenomena by the question "*why do you think this occurred?*"

Procedure. The second experiment was paper-based and administered in an actual classroom. Like in Experiment 1, the first phase was presented as a text comprehension activity in which participants were asked to carefully read three different stories, and to answer three comprehension questions about each. While the first and third stories served as distractors, the second situation (base analog) was analogous to the target phenomenon to be presented in the following phase. Three min were allotted for reading each story, and five min for answering each set of questions.

To create a strong contextual separation between the learning and transfer phases, one week later a second experimenter was presented in the class with the declared purpose of administering a hypothesis-generation activity.

The instructions for the hypothesis-generation task were identical to those of the previous experiment. While the first phenomenon for which participants had to generate explanatory hypotheses served as a distractor, the second phenomenon (target analog) was analogous to the second situation of the preceding phase. Participants had four minutes for generating hypotheses for the first phenomenon and another four minutes for generating hypotheses for the second. The post-task questionnaire, the plausibility rating scale and the invited transfer activity were identical to those of Experiment 1.

Results. Thirteen participants were excluded from the analysis for failing to complete all sections of the experiment.

Spontaneous Transfer. The percentages of participants who spontaneously transferred the base situation while generating hypotheses for the target were of 80% when both similarities were present, of 72% when there was only domain similarity, of 53% when there was only object similarity, and of 23% in the lack of any kind of surface similarity (see Figure 2). A logistic regression model revealed positive effects of object similarity (*ß* Estimate = 1.34, *SD* = 0.55, Wald *Z* = 2.45, *p* = .014) and domain similarity (*ß* Estimate = 2.17, *SD* = 0.58, Wald *Z* = 3.72, *p* = .000) on the spontaneous transfer of the base explanation. The interaction between both variables was not significant (*ß* Estimate = -0.90, *SD* = 0.81, Wald *Z* = -1.10, *p* = .268). When compared to a condition lacking both kinds of similarity, the effect of adding object similarity on spontaneous transfer did not differ from the effect of adding domain similarity (*ß* Estimate = 0.82, *SD* = 0.52, Wald *Z* = 1.57, *p* = .116).

Among the total of participants who spontaneously explained the non-additivity of volumes based on the fitting of smaller units among larger pieces, only three reported not having been spontaneously reminded of the base situation while generating hypotheses for the target. As in Experiment 1, this suggests that participants are unlikely to extrapolate the learned explanation without also retrieving the specific case in which the learned explanation was embedded.

Informed Transfer. The percentages of participants who could successfully transfer the base explanation upon explicit request were of 90% when both similarities were present, of 81% when there was only domain similarity, of 73% when there was only object similarity, and of 77% in the lack of any kind of surface similarity (see Figure 2). A logistic regression model revealed that neither object similarity (*ß* Estimate = -0.21, *SD* = 0.57, Wald *Z* = -0.36, *p* = .716), nor domain similarity (*ß* Estimate = -0.23, *SD* = 0.62, Wald *Z* = 0.37, *p* = .707) were predictors of transfer upon explicit request. The interaction between both kinds of similarities was not significant (*ß* Estimate = 0.94, *SD* = 0.95, Wald *Z* = 0.89, *p* = .324).

Plausibility. The scores received by the base analog as a reasonable foundation for explaining the target situation were of 3.7 (object and domain similarities), 3.6 (domain similarity), 3.8 (object similarity), and 3.9 (neither kind of similarity). The differences between the groups did not reach statistical significance.

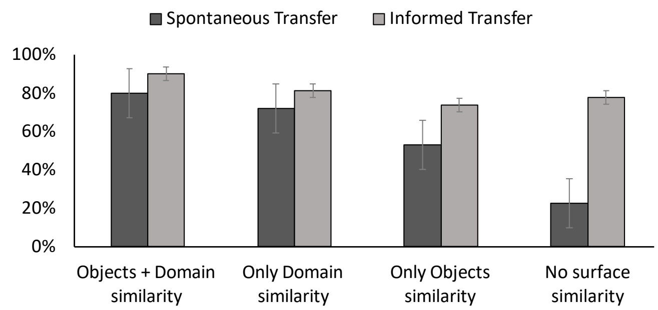

Figure 2: Spontaneous and Informed Transfer rates, Experiment 2.

Discussion. As in Experiment 1, object and domain similarities were capable of boosting spontaneous analogical transfer during hypothesis generation. Also as in Experiment 1, there was no evidence of an interaction between the effects of both kinds of surface similarity on spontaneous analogical transfer.

In interpreting the observed lack of interaction between both variables obtained in Experiment 1, we had conjectured that the similar objects condition could have benefitted from the possibility that the molecular explanation provided for the "swimming pool scenario" might have elicited the chemistry domain despite our efforts to render its cover story (swimming pool management) as removed as possible from said domain. The base-target inversion operated in Experiment 2 overcame this potential confounding, predictably lowering the spontaneous transfer rate of the object similarity condition. However, the results once again failed to reveal an interaction between the effects of objects and domain similarity, therefore failing to support Ripoll´s (1998) theoretical conjecture that in the lack of domain information that could aid in further constraining memory search, the sole presence of object similarities would fail to reliably support analogical retrieval.

On the other hand, we had conjectured that the base-target inversion would also render the post-access demands more equivalent across conditions, thus allowing to more conclusively interpret the differential rates of spontaneous transfer as indicative of the effects of the manipulated variables on the retrieval component of analogical transfer. The fact that in Experiment 2 objects and domain similarities had similar effects on spontaneous transfer suggest that both variables can exert a similar weight during the spontaneous retrieval and application of the base explanatory structure during a hypothesis generation task.

General Discussion

Hypothesis generation is a fundamental cognitive activity. From the most mundane scenarios to the most ambitious scientific endeavors, the generation of plausible causal explanations can capitalize on the retrieval of structurally related items whose known explanatory structure could be tentatively extrapolated to the current situation.

While the computational processes involved in analogical retrieval have received a great deal of attention, most of what is known comes from problem-solving activities, or else from pragmatically void memory tasks. Within this literature, a robust finding concerns the reliance of the retrieval systems on surface-level cues instead of deeper structural commonalities. There is some evidence that both similarity of objects and similarity of domains affect spontaneous access, but it is not yet clear how these two kinds of surface similarity interact to aid analogical transfer in the service of generating causal explanations, especially among novice participants.

With the aim of filling this gap at the intersection of the hypothesis-generation and analogical reasoning literatures, in two experiments we factorially manipulated object and domain similarity to assess their impact on transferring the explanatory structure of a base situation. Despite some differences between Experiment 1 and Experiment 2 in both the experimental setup and the materials used as base and target situations, the results from both experiments converge in demonstrating that either kind of similarity suffices to raise transfer rates considerably.

The scarcity of behavioral studies trying to isolate an effect of domain similarity may stem from assuming that its correlation with object similarity is so high that the expressions “cross-domain” and “superficially dissimilar” could almost be employed interchangeably. While it seems true that within certain regions of knowledge (e.g., astronomy) within-domain situations tend to involve similar entities and vice-versa, there are also domains within which situations can vary to a great extent in terms of their constituent elements (e.g., the biological domain includes both the rhythmic light pulses emitted by a firefly and the cardiac cycle of the human heart). In the computational modeling arena, the lack of a specialized treatment of domain similarity may respond not only to the empirical base provided by behavioral studies, but also to the fact that domain representations do not tend to correspond exactly to any concrete expression of a situation’s description, being typically inferred by the cognizer. Hence, its computational implementation may imply a higher theoretical cost than that implied by operations on propositional statements (Ripoll, 1998).

One question that remains open in the present research concerns how analogical transfer is affected by the interaction between domain similarity and the specific activity that the analogizer is pursuing. The task of formulating explanatory hypotheses for phenomena that fall within culturally established domains may render this surface cue relevant to drive the search process, as the causes of certain phenomena can be recruited within the space of a knowledge domain. Perhaps in other types of activities for which a domain space is less relevant for recruiting knowledge (e.g., generating persuasive arguments or solving insight problems), this surface cue may lose strength during the search process. In line with recent results highlighting how analogical processing can vary a function of the overarching task within which analogical transfer is being evaluated (see e.g., Trench et al., 2020), future research should assess the effects of object and domain similarity across target activities different from the one investigated in the present study.

In terms of educational implications, the fact that exploiting domain information about a target phenomenon aided analogical transfer could be taken to indicate that instructors should emphasize these aspects of target phenomena so as to promote the retrieval of useful information. However, highlighting the domain of a target phenomenon can hinder the retrieval of base analogs which do not belong to the target domain, but which could nevertheless inspire potentially relevant explanations. In those cases where one can anticipate the unavailability of useful information within the target domain, a useful strategy for retrieving distant analogs can consist in postulating promising domains wherein source analogs seem likely to be found, and circumscribing search within those domains (Trench et al., 2016).

Having knowledge that remains inaccessible when it could potentially illuminate an unknown phenomenon is a limitation that people face on a daily basis when trying to generate hypotheses. Understanding the conditions under which this useful knowledge will become activated still represents one of the biggest challenges of cognitive science and education.

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