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Opinion

# Creative problem solving in knowledge-rich contexts

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**Creative problem solving (CPS) in real-world contexts often relies on reorganization of existing knowledge to serve new, problem-relevant functions. However, classic creativity paradigms that minimize knowledge content are generally used to investigate creativity, including CPS. We argue that CPS research should expand consideration of knowledge-rich problem contexts, both in novices and experts within specific domains. In particular, paradigms focusing on creative analogical transfer of knowledge may reflect CPS skills that are applicable to real-world problem solving. Such paradigms have begun to provide process-level insights into cognitive and neural characteristics of knowledge-rich CPS and point to multiple avenues for fruitfully expanding inquiry into the role of crystalized knowledge in creativity.**

## Highlights

Creative problem solving (CPS) relies on the reorganization of existing knowledge to serve new, problem-relevant functions.

Extant creativity research, especially brain-based research, largely does not reflect the knowledge-rich contexts in which the application of previously-acquired knowledge is critical, as is frequently the case in real-world CPS.

Knowledge-rich CPS frequently involves expertise, and can be fruitfully studied in expert participants. It can also be studied in novices when content knowledge is available as a component of the experimental paradigm.

Behavioral and neuroimaging CPS paradigms based on analogical transfer can provide process-level insights into knowledge-rich CPS in non-experts. The transfer-based heuristic prototype paradigm has the potential to be flexibly applied across diverse domains of knowledge.

Better understanding of CPS as a process, especially via analogical transfer, has timely potential to inform education and creativity training.

## Real-world CPS requires crystalized knowledge

The extraordinary capacity of humans to generate creative solutions to problems, which was first essential to our competition with other species, has taken on renewed interest as we enter a new phase of competition (and collaboration) with ‘thinking’ machines. While as many as 50% of current jobs in the USA are projected to become obsolete in the next two decades, substantial growth is projected in creative sectors [1]. As interest in CPS has increased among researchers and educators, as well as in industry, CPS has been primarily operationalized via knowledge-lean measures of creativity [2–5] that seek to minimize or eliminate the requirement of specific knowledge content for creative performance. In the classical creativity task, the **alternative uses task (AUT) (**see Glossary), for example, participants are evaluated on their capacity to originate divergent ideas (e.g., grinding up a brick to use as fairy dust in a costume), as opposed to their ability to apply knowledge transferred from other contexts. Another commonly used assessment, the figural Torrance Test of Creative Thinking (TTCT), requires participants to use a given shape/figure (e.g., a teardrop shape) as a basis to create their own figure. As with the AUT, generating novel figures emphasizes origination over the application of **crystalized knowledge**. By contrast, the real-world value of CPS – including in the growing creative sectors of the innovation economy – is almost always in knowledge-rich contexts in which knowledge acquired through prior learning (e.g., education and life experience) across multiple domains can be flexibly applied to solve novel problems. In other words, real creative solutions frequently require the use of knowledge, which is not required – and is indeed deliberately avoided – in standard creativity measures.

Models of creative thinking stress the importance of knowledge to creativity [6–9]. Knowledge provides a basis for interpreting new information. Moreover, previously acquired knowledge must be recombined and reorganized to produce the new knowledge that allows the generation of novel ideas [10]. Empirically based observations have suggested that, after controlling for some

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intellectual and personality differences, a fundamental difference between more- and less-creative individuals may be the knowledge that the individual transfers to generate solutions when faced with a problem [8]. Knowledge (drawn from both the same domain as the problem and from other domains) is integral to the process of generating creative solutions in ecologically valid settings [8,11–13]. These empirical and theoretical indicators point to extending the assessment of creativity beyond knowledge-lean paradigms as a priority for developing models of CPS that can be applied to knowledge-rich contexts [14].

Here, we use the term **knowledge-rich** CPS to describe problem solving in which the application of crystalized knowledge plays a prominent role. By contrast, **knowledge-lean creativity** de-emphasizes crystalized knowledge. The term, crystalized, generally connotes knowledge that is retained in memory beyond the more fluid short-term stages (e.g., working memory). Just as the distinction between short- and long-term memory is not uniformly agreed upon, the term, crystalized knowledge, is used somewhat variably. Our usage of the term is inclusive of knowledge that is learned and then retained over an interval of hours or days, rather than only including knowledge that is retained across years or decades. Note that the knowledge-rich versus knowledge-lean distinction is separate from the parameter of expertise. Knowledge-rich CPS frequently involves expertise, and can be fruitfully studied in expert participants, but does not require expertise, and can also be studied in novices when content knowledge is available as a component of the experimental paradigm that is learned, retained, and then applied within the paradigm.

## Classic creativity assessment

Since Guilford (1956) [112] first proposed **divergent thinking (DT)** and **convergent thinking (CT)** processes as two core processes of creative thinking, a variety of paradigms and materials have been employed to explore the cognitive and neural mechanisms of these processes. As a measure of CT, a **compound remote associates measure (CRA)** was developed patterned after the remote associates test (RAT) devised by Mednick [15,16]. These problems consist of three words (e.g. pine, crab, and sauce), and require the participant to think of a single solution word (apple) that will form a familiar phrase with each word (pineapple, crab apple, and apple sauce). The CRA is well-suited for EEG and neuroimaging research because it involves brief timing epochs and the availability of a large number of normed task items supporting well-powered designs, which has contributed to wide use of CRA for cognitive and brain-based studies of the CT component of CPS [17,18]. Notably, although the CRA presents puzzles to be solved, it is not a measure of problem solving in a traditional sense because (unlike classical CPS paradigms such as the candle problem, or the nine-dot problem) [16,17]), it emphasizes word associations rather than solution generation to meet the situational demands of a presented problem.

Even greater attention has been directed to the DT component of creativity [19–26]. In DT tasks, participants generate multiple original responses to an open-ended prompt [3,4]. Although they have been used to test a range of hypotheses, DT paradigms are largely limited to two primary measures, AUT [27] and TTCT [28]. While these tasks are frequently associated with creativity and have been shown to predict both past and future creative achievements [3,4], they are not typically devised to measure problem solving: prompts typically do not represent problems to be solved, they represent invitations to consider divergent ideas (e.g., possible uses of a common object, possible consequences of a fictional/counterfactual circumstance). Low ecological validity clouds inferences about the relationship between these measures and real-world creativity [29].

A feature that the above-described paradigms (as well as classic CPS paradigms like the candle problem) have in common is that they were devised to de-emphasize content knowledge. The

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intent of these knowledge-lean task designs is to separate any advantage/disadvantage of possessing/lacking specific prior knowledge from creative performance [30]. While research employing these paradigms has afforded considerable insights into cognitive and neural bases of creative thinking, and although some studies have shown that these tasks correlate with crystalized knowledge assessed via measures of vocabulary [31], the extent to which this research generalizes to CPS in knowledge-rich contexts remains unclear. Thus, nontrivial elements of how creativity is applied to solve problems have remained largely unexplored.

The research gaps concerning knowledge-rich CPS and lack of ecological validity are most evident in brain-based research, where pragmatic constraints of the neuroimaging environment have limited the number and variety of CPS measures even more so than in behavioral research [18,29,32,33]. Generally, neither the problem materials themselves nor the testing procedure are designed to include previously learned knowledge or to reflect real-world problems [34]. Investigation of the neural correlates of CPS requires researchers to adapt creativity tasks to meet the constraints imposed by cognitive neuroscience research – assessing well-defined cognitive processes, repeated over many trials.

## Creative thinking within domains of expertise

A somewhat variegated body of creativity research has sought to include previously learned knowledge in ways that reflect real-world creativity, and to compare neural mechanisms of creative performance between experts and novices in specific domains of expertise [35–39]. This kind of research is valuable and provides some insights into creative performance within a domain. Previous studies of this kind have largely focused on artistic creativity, such as music improvisation, drawing, and literary creativity, and have identified differences in functional brain activity and connectivity between experts and novices in these tasks [35–39]. Importantly, artistic performance paradigms are generally not devised to distinguish crystalized knowledge from procedural or implicit knowledge/memory that supports artistic performance. Such paradigms are thus somewhat different from what we refer to here as knowledge rich. Relatedly, artistic performance does not represent problem solving in a traditional sense. More reflective of problem solving have been studies comparing experts and novices in design and engineering domains [35,40].

Research conducted with domain-expert participants is valuable for demonstrating that knowledge supports problem solving, and we would advocate for more such work. However, focusing on a specific domain of expertise has some inherent limitations on both the qualified participant pool and the generalizability of the findings. Experts and novices may differ along many dimensions in their knowledge representation [40–42], and focusing on the expert versus novice distinction often does not inform mechanistic questions concerning specific aspects of knowledge, and specific modes by which knowledge is deployed, that enable successful CPS. Paradigms that allow investigation of the use of knowledge to develop creative solutions in non-experts have the potential for broader sampling and more generalizable inferences about CPS in knowledge-rich contexts. Such work may help to inform general processes that support CPS.

## Creativity and analogical transfer

Analogical transfer, that is, the application of knowledge from prior experience (source) to a new problem (target) based on similarities in the situational structures between the source and target, has been shown to underlie real-world CPS in multiple contexts and knowledge domains [43,44]. While analogical transfer has long been considered an essential cognitive mechanism for CPS [45–47], analogy paradigms have not been nearly as prominent in creativity research as the

## Glossary

**Alternative uses task (AUT):** a task that aims to measure divergent thinking by asking participants to think of novel uses for everyday objects.

**Compound remote associates measure (CRA):** a task that aims to measure convergent thinking by providing participants with three unrelated words (e.g., pine, sauce, and crab) and asking them to think of a fourth word (in this case, apple) that forms a compound association with each of the given words.

**Convergent thinking (CT):** requires homing in on a limited number of response (often only one correct solution) from a number of possible alternatives.

**Crystalized knowledge:** knowledge that is learned and then retained across years, decades or an interval of hours or days.

**Divergent thinking (DT):** refers to expansive generation of novel ideas. One critical component of creative cognition.

**Knowledge-lean creativity:** creativity in which the application of previously-learned knowledge is de-emphasized relative to origination of novel and/or divergent responses.

**Knowledge-rich creativity:** creativity (including creative problem solving) that takes the form of applying (often via transfer) previously learned knowledge, for example, in a novel manner, or in a novel context.

**Prototype heuristic task:** a task intended to simulate real-life CPS which addressed important problems by drawing inspiration from other things.

above-noted measures of CT and DT. This is somewhat puzzling given that analogy appears to represent a more balanced combination of CT and DT than more frequently used tasks such as the CRA and AUT [48,49] and the generally accepted notion that CT and DT operate in concert (not separately) to accomplish CPS [14,48–50]. Likewise, creativity has generally been a secondary consideration in analogy research, which has more often emphasized analogical transfer as a mechanism for learning in development and education, and for analytical reasoning and problem solving [51,52]. Analogy research that has directly considered creativity, particularly brain-based paradigms, has largely presented analogies in the 'A is to B as C is to D' format (e.g., puppy is to dog as spark is to fire) [46]. These paradigms generally require participants simply to judge the analogical validity of four presented terms or, more rarely, to generate the C and/or D terms of the analogy [46,53,54]. Thus, this work has not usually sought to reflect real-world problem solving; the stimuli do not present situational demands/problems to be addressed, and in many cases do not pertain to functional/demand-relevant attributes of words or relations (e.g., 'high is to low as happy is to sad'). These paradigms also de-emphasize the kind of knowledge transfer that characterizes real-world CPS because the only content that is relevant for participants to consider is immediately present in the stimuli while participants are responding. There is no need to transfer information stored in memory from a separate, previously encountered context.

## Analogical transfer in knowledge-rich CPS

Knowledge-rich CPS can be studied in novices by providing knowledge as a component of experimental paradigms in which knowledge acquisition in one context must be transferred to address a problem presented in another context. Though the above-described analogy paradigms have provided several important insights into analogical creativity, these formats greatly constrain the search space for analogical transfer – with all possible relevant information immediately at hand in most cases. The real-world CPS requirement of searching memory for knowledge that can be successfully transferred to a problem is thus not strongly represented in these paradigms. Paradigms focusing on the generation of creative design ideas have more fully engaged analogical knowledge transfer.

Analogy appears to be a powerful problem-solving mechanism in design fields [55–57]. When faced with a problem to solve in the present (target), a designer may look to similar problems in the past (source) and establish an analogical mapping between the target and the source [57]. The distance in semantic space between the source and the target (roughly corresponding to how dissimilar they seem from each other on the surface) provides an index of how creative a design solution is [58–61]. Indeed, studies of real-world design indicate that more creative results come from analogical reasoning from a distant source [62]. Creative design solutions require the designer to inhibit attention to surface characteristics and look for more abstract structural connections [39]. Visual analogy has also shown efficacy in fostering creativity in design education [63], and providing visual displays with structures analogous to viable design solutions improves the quality of design across the board, and is particularly beneficial for novice designers [41].

To advance the study of knowledge transfer in CPS, we developed a **prototype heuristic** paradigm that focuses on creativity in analogical transfer, and can also be implemented in ways that involve substantial memory search demands [64–68]. Many historical examples demonstrate creative solutions that addressed important problems by drawing inspiration from the adaptive feature optimization of biological species (i.e., bionic imitation) [69]. A relatively modern example is the engineering of water and grime-dispersing perturbations for nonstick surfaces of buildings and vehicles, which was inspired by the nonstick surface of the lotus flower's petals [70]. We use the term, prototype, to refer to a source exemplar (a lotus flower pedal in the example above) possessing elements that achieve a function similar to the function required to solve the problem at hand [71]. We describe these prototypes as heuristic in the sense that they enable discovery by providing a loose framework for novel solution generation [71–77]. In this paradigm, participants are first exposed to information containing potential prototypes. After a delay (often on a separate day), they are asked to generate solutions to a set of scientific problems, such that participants must retrieve and transfer the relevant previously learned information. Real scientific problems were collected from several forms of media, including books, television, and the internet. The original solutions to each of these problems were artificial devices that were designed based at least in part on prototypes from the natural world (Box 1) [75]. All problems are loosely defined with open-ended prompts indicating the kind of solution that was needed. Participants in the task are not informed of any prior connections between the prototypes and scientific problems, and data for any trial on which a participant reports prior familiarity with the solution are excluded. Thus, for the participants, the connections between the biological features of the prototype and the problem solutions reflect novel associations [65,71–77]. This paradigm is intended to bring the study of CPS closer to the knowledge-rich contexts that characterize real-life CPS, particularly in scientific innovation.

Transfer in the prototype heuristic paradigm is an instance of analogical transfer. That is, relational structures (i.e., the ways that elements relate to each other) are mapped between a target (the problem to be solved) and a source (the prototype) [44,78–81] (Figure 1). According to the structure-mapping theory of analogy, analogical transfer proceeds by establishing a structural alignment between two represented situations and then projecting inferences [43]. Importantly, the prototype can, and usually does, also involve many problem-irrelevant elements (e.g., the color of a lotus flower would be irrelevant in the above example) [72,75,77]. Thus, as in prior analogical transfer paradigms [82], the prototype heuristic paradigm requires participants to identify only the relevant elements of the source amid the larger set of problem-irrelevant information. This aspect of the paradigm contributes at least modestly to ecological validity because in real-life CPS the clues to solve a problem are commonly submerged in a large body of irrelevant

Box 1. Examples of scientific problems

(i) **Wash dust and dirt off of a car**

**Situation:** it is not easy to wash dust and dirt off of a car with water, but adding chemical detergents is prone to corroding the car surface.

**Scientific problem:** how can you design a car surface where it is easy to wash off grime with water?

**Prototype:** the surface of lotus leaves has many minute protuberances, so water droplets cannot disperse on the leaf surface. They can only ball up and roll off, and these water balls carry off grime.

**Reference solution:** the car surface forms minute protuberances (like a lotus leaf) after spray painting.

(ii) **Antislip athletic shoes**

**Situation:** tennis players are very prone to slipping in smooth plastic court, and can get injured.

**Problem:** how can you give the rubber soles of athletic shoes an anti-slip function?

**Prototype:** an octopus has many concave sucker pads, and can firmly attach to object surfaces, preventing slippage.

**Reference solution:** design sucker pad-shaped indented grooves on the soles of an athletic shoe in order to prevent slipping.

(iii) **Biofertilizer**

**Situation:** applying chemical fertilizers can increase the productivity of agricultural work; however, applying chemical fertilizer can also damage soil fertility, and is harmful to people's health. However, folk fertilizers (wood ash, manure, etc.) are not fully hygienic.

**Problem:** how can you obtain a fertilizer that makes farm work productive without applying chemical fertilizers or folk fertilizers?

**Prototype:** the nitrogen-fixing bacteria at the roots of legume plants can synthesize nitrogen fertilizer from the nitrogen in the air. They form root nodules containing nitrogen fertilizers in the roots of the legume plant in order for the legume plant to supply synthetic nitrogen fertilizer.

**Reference solution:** use the nitrogen-fixing bacteria of the roots of legume plants to increase the soil nitrogen fertilizer.

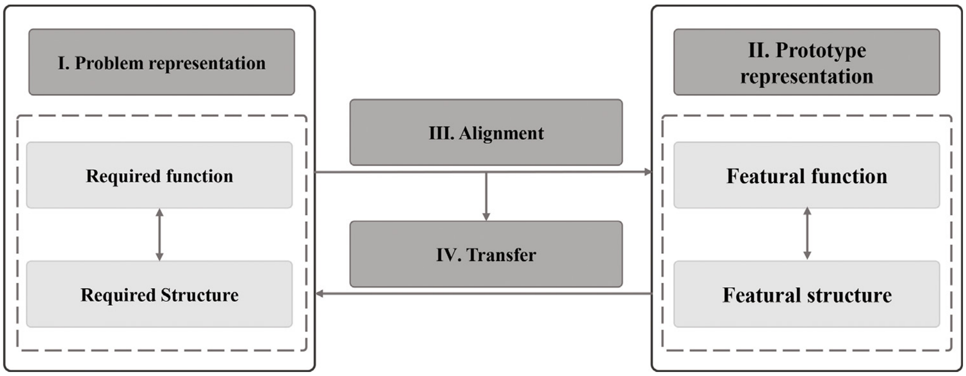


Figure 1. A cognitive schematic of creative problem solving in the prototype heuristic paradigm. In the prototype heuristic paradigm, participants are (I) presented with a problem and (II) search previously learned prototypes in order to (III) identify a prototype that achieves a function that aligns with the required function of the problem, indicating that (IV) the featural structure of the prototype can be transferred to construct a scientific innovation that solves the problem. Adapted, with permission, from [71].

and distracting information. The prototype heuristic paradigm can incorporate two kinds of irrelevant information. First, participants can be presented with a large set of candidate prototypes (this can be done minutes, hours, or days in advance of being asked to solve problems [73]. In this case, the prototypes that do not successfully align with a given problem constitute irrelevant and potentially distracting information. Alternatively (or in combination), the paradigm can be implemented with irrelevant information included describing the prototype in order to place greater demand on the capacity to distinguish alignable features from nonalignable features when searching learned information in memory [75,77]. By placing greater demand on memory search for alignable features of prototypes, and affording greater contrast between signal and noise in the alignment process, inclusion of irrelevant information has helped further clarify the importance of successful alignment to CPS [72,75,77].

The prototype heuristic paradigm is well-suited to neuroimaging – indeed it was devised for this use – with relatively brief task epochs to enable precise timing, and with a large number of task trials developed. Indeed, we have conducted several neuroimaging studies using this paradigm. Classic analogy paradigms that involve transfer of prior knowledge that have a more narrative format and relatively few trials have generally not been well suited for imaging. The prototype heuristic paradigm thus helps to fill theoretical and practical gaps, especially for neuroimaging research, affording a window into transfer-based CPS in knowledge-rich contexts.

## Neural characteristics of creative thinking in knowledge-rich contexts

Outside the mainstream of knowledge-lean creativity research, some insights have been gained into neural mechanism of creative thinking within domains of expertise by applying neuroimaging to compare experts and novices [35,39,83,84], including in artistic domains, though extant results are somewhat heterogeneous. Compared to inexperienced writers, professional writers exhibited stronger activation within the DMN in a literary text continuation task [84]. Moreover, experts showed significantly stronger deactivation of the executive control network during poetry composition, including in the dorsolateral prefrontal cortex (DLPFC), suggesting they may more effectively suspend cognitive control [83]. Studies of musical improvisation have reported that domain expertise is characterized by deactivation of the right DLPFC associated with executive processing [85]. Improvisation training was positively associated with functional connectivity of the bilateral DLPFC, dorsal premotor cortices, and pre-supplementary areas. The greater functional connectivity seen in experienced improvisers may reflect a more efficient exchange of information within associative networks of importance for musical creativity [85].

While these studies are informative, it is likewise noteworthy that considerable domain specificity was observed in the neural circuits involved in creative performance across the domains considered in this study. Although this research indicates characteristics of creative performance within domains of expertise, it focused on creative performance, but not creative problem solving as such. Thus, the implications for knowledge-rich CPS remain somewhat unclear. Likewise, because separate paradigms were used in the studies that were considered, and because those studies focused on separate groups marked by particular expertise (which is likely related to other differences in interest and ability), it is difficult to draw strong conclusions about the nature of neural differences observed between domains.

Beyond artistic domains, neuroimaging has begun to indicate neural characteristics of expertise in creative design. Research in a group of graduate design and engineering students showed that the presence of inspirational stimuli intended to induce transfer of relevant concepts to presented design problems resulted in more fluent idea generation and were associated with a distinct pattern of brain activation in bilateral middle temporal gyrus (MGT), superior temporal gyrus (STG) and precuneus, which the authors interpreted as indicating increased memory retrieval and semantic processing [56].

Recent research has explored neural bases of knowledge-rich CPS via analogical transfer in the prototype heuristic paradigm [65,67,72–74,86]. Overall, this work indicates neural characteristics that overlap with characteristics of DT and CT, but also provides neural insights into how crystalized knowledge systems (e.g., for semantic retrieval and integration) operate in conjunction with elements of DT and CT. CPS during the prototype heuristic paradigm engages regions that are also engaged during DT, such as left DLPFC, which may support creativity via the flexible guidance and monitoring of attention and working memory [67,87]. In the prototype heuristic paradigm, participants have to maintain the required function of the problem while searching memory for alignable prototypes, suggesting the importance of both flexibly guided attention and working memory maintenance of problem constraints in this paradigm. In addition to regions associated with DT, several regions linked to CT, such as the right STG and the left MTG are also recruited in the prototype heuristic paradigm [72,74]. Right STG is associated with finding convergent solution words that satisfy multiple associative constraints in the CRA [5,16]. Like the CRA, the prototype heuristic paradigm requires convergent constraint satisfaction, as the problem solver first represents the required function of the problem, and then uses this required function to search their memory for alignable features in learned prototypes. Particularly, some regions associated with semantic retrieval and integration, such as the left precuneus and left angular (AG) are also engaged during CPS in the prototype heuristic paradigm (Figure 2) [73,86,87]. Precuneus is frequently engaged during semantic retrieval [88–92]. AG appears to support retrieval and integration of memories [93–97].

Although some right-sided activity has been observed, findings for the prototype heuristic paradigm have primarily been left sided [67,73,74,86,87]. This may reflect the emphasis on crystalized semantic knowledge in analogical transfer. Regions activated in analogy such as the left AG gyrus [86,87] and the left MTG [72] are connector hubs in semantic neural networks [98–100]. Left-sided activity in the prototype heuristic paradigm is consistent with predominantly left-sided findings in previous analogical reasoning research, including a body of work that has implicated left frontopolar cortex in relational integration during creative analogy verification and generation [46,54].

## Concluding remarks and future directions

Although creative solutions in the real world often involve transfer of previously learned knowledge to a problem at hand, the paradigms used to operationalize creativity in the laboratory, and especially in neuroimaging, generally do not. Paradigms based on analogical transfer can help address this gap by situating innovative scientific CPS in the context of transferable knowledge. Such paradigms, including the prototype heuristic paradigm, represent a step toward greater consideration of knowledge-rich contexts and more ecologically valid investigation of CPS in the laboratory. We hope that the insights that extant analogical transfer paradigms afford can help to demonstrate the value to be gained through further development of knowledge-rich CPS paradigms suitable for neurocognitive research.

Research within domains of expertise has the virtue of measuring the application of crystalized knowledge that is more organically acquired (via experience and education). However, any such study is necessarily limited to a specific domain of expertise and to a largely self-selected group of participants, who may differ from experts in other domains, and from nonexpert populations, in multiple confounding ways. Thus, it is important that CPS also be investigated in nonexperts. This requires the development of paradigms that involve knowledge acquisition and subsequent transfer of knowledge without the precondition of expertise. Investigating CPS in novices also provides substantial advantages for experimentally manipulating the amounts of knowledge provided, and the ways in which knowledge is acquired. Such experimental control can elucidate CPS at the process level by enabling greater insight into the particular elements of crystalized knowledge that support CPS. A more granular understanding of knowledge acquisition, representation, and application in CPS would inform ongoing efforts to bolster CPS in educational and professional training contexts [55,101].

The prototype heuristic paradigm is an exemplar of knowledge-rich CPS measurement in novices, which has the potential to enable insights at the process level, including via neuroimaging. Comparing across domains of knowledge, while minimizing the confound of paradigmatic differences, has potential to provide insights into domain-general elements of knowledge-rich CPS (see Outstanding questions). The heterogeneity of extant paradigms used to study creativity across different domains of knowledge (e.g., in different artistic fields and design sciences) has substantially impeded attempts to meta-analyze and draw generalizable inferences.

Although the neuroimaging data thus far available point to some instructive similarities and differences between knowledge-rich CPS in knowledge-rich domain and more knowledge-lean paradigms used to operationalize creativity and analogy, more work is needed. Future work on knowledge-rich CPS should seek to characterize the respective roles of semantic retrieval and integration resources, and more fully engage network neuroscience approaches that have spurred recent advances in neurocognitive understanding of network dynamics in DT [102,103] and of semantic memory networks that subserve search and retrieval of learned knowledge [104–108]. Such work can enable informative comparisons of the connectomics and functional dynamics that characterize knowledge-rich CPS to the network characteristics of other forms of creativity (see Outstanding questions).

More generally, research on CPS should advance toward real-life CPS, particularly in domains of knowledge that have important applied implications. In education for example, we aim teach students to acquire knowledge and then transfer this knowledge to creatively solve problems in daily life. Why is it that students exposed to the same knowledge differ in the extent to which they creatively apply what they have learned? Continued advances in empirical approaches for studying knowledge representation may thus be critical to advancing our understanding of

### Outstanding questions

In what ways do the cognitive operations that support creativity in knowledge-rich contexts differ from or overlap with those that support creativity in knowledge-lean contexts? How might crystalized knowledge interact with memory, attention, and cognitive control, which are frequently associated with knowledge-sparse creative problem solving?

Current neural models of creativity, which are based almost exclusively on studies of knowledge-lean paradigms, emphasize the interaction between the brain's executive control network and default mode network. To what extent do these network dynamics support knowledge-rich CPS?

Why are some individuals better able to flexibly apply the knowledge they have acquired through experience, education, etc. across multiple domains to solve novel problems? Can knowledge-rich CPS be improved through mnemonic training in laboratory and educational settings? Leveraging computational linguistics and network science to explore individual differences in knowledge representation, and within-subject changes in knowledge representation after training, might enable advances on these questions.

Can knowledge-rich CPS be improved through creative state manipulations? For example, instructions to think creatively have shown substantial efficacy for improving creative performance in knowledge-sparse paradigms. Relatedly, to what extent do trait affective influences, including creativity anxiety (anxiety specific to generating creative ideas) impact knowledge-rich CPS.

Do neural insights identified for analogical transfer in the heuristic prototype paradigm translate to other implementations of knowledge-rich CPS, within and across domains of expertise?

Can behavioral and/or brain-based interventions that support analogical transfer in the heuristic prototype paradigm be used to improve other knowledge-rich CPS in the laboratory and/or educational settings?

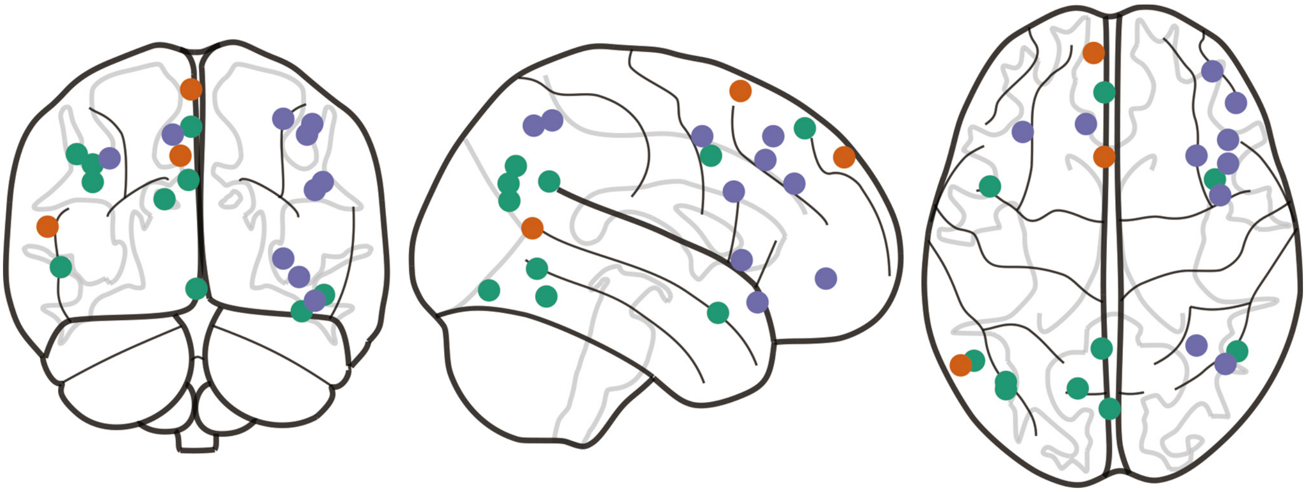


Figure 2. Brain regions engaged during creative thinking in knowledge-rich contexts. The green dots indicate regions engaged in knowledge-rich creative problem solving in the prototype heuristic paradigm [62,64,78,80]. The orange dots indicate regions involved in analogy generation task [103]. The purple dots indicate regions involved in creative thinking in domains of expertise across musical creativity, drawing creativity, and literary creativity [34,75,77].

these differences in creative transfer [13,109]. Recent work applying methods from computational linguistics and network science is providing novel quantitative insights into the role of knowledge and memory structure in creativity [108,110,111]. Future work should further leverage these methods to examine individual structures of knowledge representation, how differences in these structures relate to real-life CPS, and how such computational methods can be used to bridge across cognitive and neural mechanisms related to real-life CPS [107] (see Outstanding questions).

Perhaps most broadly, exploration of knowledge-rich CPS can encourage greater appreciation of the role crystalized knowledge has in creativity. The increased emphasis on knowledge-lean measures of fluid cognition (rather than crystalized knowledge) in the study of both creativity and intelligence, should not lead us to forget how important it is to remember. Taking the value of semantic search and retrieval more fully into account can also help to motivate future efforts to determine whether training and facilitating mnemonic retention and search can bolster CPS in laboratory and educational settings.

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## Declaration of interests

No interests are declared.

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