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REVIEWS

Scientific Life

Promoting Individual and Collective Creativity in Science Students

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Creativity is a scientific skill necessary to develop a successful research career. We expose the importance of a growth mindset, divergent, lateral, and associative thinking, serendipity, and being part of a nonhierarchical and diverse research team to improve both individual and collective creativity.

Creativity is a Scientific Skill

Scientists produce new knowledge by applying the scientific method. In addition to making observations, a first step in generating this knowledge is to have innovative ideas. The transition from students – recipients of knowledge – to scientists – creators of knowledge – occurs in graduate school; a metamorphosis not without frustrations and even trauma [1]. Universities do train science students properly in critical, logical, and analytical thinking (i.e., evidence-based, convergent thinking; Figure 1). These skills are essential for the application of the scientific method. However, science students are often poorly educated in creative thinking. Instead, they are trained to accumulate knowledge in academic curricula that seem to block their creative potential. Creativity is an evolved cognitive mechanism for abstracting, synthesizing, and solving nonrecurrent problems and is crucial for performing cutting-edge science [2]. Unlike what many students and scientists think, creativity and intelligence are skills that can be developed. Carol Dweck proposed that these skills can be stimulated through effort and resilience, by embracing challenges and learning from criticisms (i.e., with a growth mindset; Box 1). Growth mindset interventions have improved performance in high school students [3], and we argue that fostering a growth mindset in the laboratory will enhance student creativity.

Tools for Creative Thinking

Some of the tools needed to develop these creative skills are divergent, lateral, and associative thinking. Divergent thinking consists of the generation of numerous options, regardless of whether they are logical or not (Figure 1). The main barriers faced by many graduates in the generation of ideas is their self-criticism, self-censorship, and fear of failure. Graduate students and advisers need to understand that, in the first phase, the generation of ideas must be separated from evaluation to try to minimize negative thinking and premature self-criticism. Rozenkrantz *et al.* [4] experimentally demonstrated that subjects who received a placebo (a harmless, odorous substance that supposedly enhanced their creativity) increased their problem-solving ability thanks to a reduction in self-inhibition. Therefore, students must trust in their creative potential and develop a creative attitude from the beginning. Brainstorming activities to reduce students' self-inhibition are crucial to promote individual creativity and to improve group performance.

Lateral thinking, a term coined by Edward de Bono, uses completely radical new perspectives to solve problems (Figure 1). This way of thinking attacks the problem by 'cutting the Gordian knot', that is, to find a solution far from the rigid standards imposed by the steps of convergent thinking [5]. For instance, the use of archival material (e.g., personal photographs and herbarium specimens) to examine changes in flowering phenology for the assessment of climate-change impacts was initially an unorthodox approach [6]. Being open to using unconventional procedures, chance, and serendipity are needed to foster creativity. Unexpected results can provide new insights into existing problems or clues to solving them. Sometimes, a problem in the researcher's head is serendipitously solved in a completely unexpected way. For instance, the finding of mobile genetic elements by Barbara McClintock happened while she was studying chromosome breakage in maize under the common assumption that genes had a fixed position in the chromosomes. Her unexpected finding opened new perspectives in the study of the genome. Alternatively, a researcher can discover a phenomenon by chance that was initially not in her head. Many keystone species, for example, starfish, sea otters, and wolves, were serendipitously discovered by detailed field observations or removal interventions. Serendipity, however, is not just luck. It is essential to be curious and inquisitive, open to opportunity, and not to ignore atypical or incongruent results. It is crucial to maintain curiosity and explore these unusual results in order to find explanations that might coincidentally lead to an unexpected finding.

Associative thinking consists of integrating, merging, and recombining ideas that initially have no connections or are even opposed (Figure 1). Synthesis sciences, such as ecology and evolutionary biology, have promoted this type of thinking. As Scheffer [2] remarks, the most difficult challenge is to find the ideas that deserve to be connected. To promote associative thinking, it is worthwhile considering similar problems in other fields, for example, by reading unrelated papers and attending seminars, to expose oneself to new ideas, and to use literature, analogies, and metaphors as inspirational elements. For example, network theory has been useful in fields as disparate as neurobiology, food web ecology, telecommunications, and social sciences. The Red Queen hypothesis of species coevolution represents an

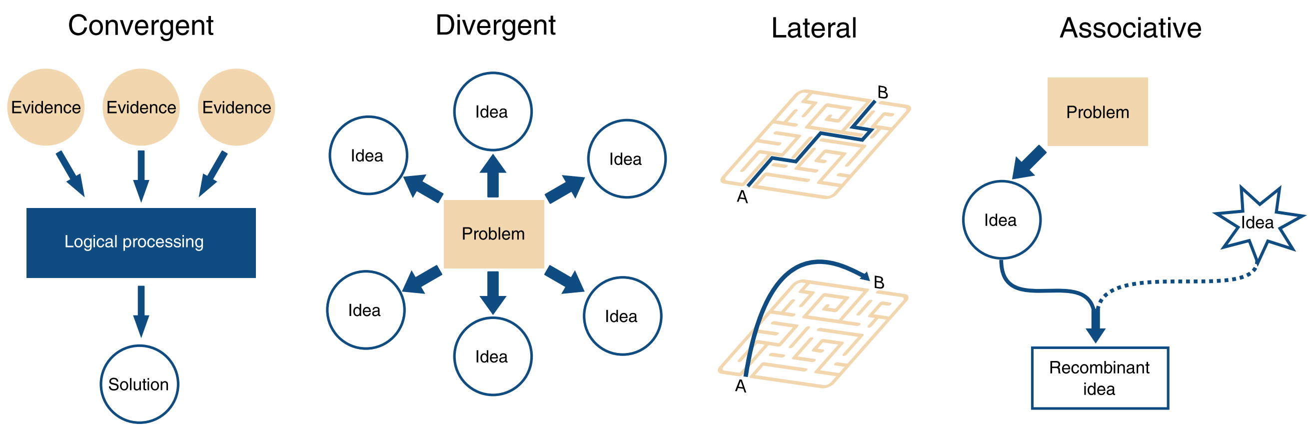

Figure 1. Types of Thinking. Convergent thinking finds solutions based on evidence through critical, logical, and analytical steps. This type of thinking represents the hallmark of science. Divergent thinking consists of generating numerous options, regardless of whether they are logical or not, to solve a given problem. This thinking type is useful for proposing working hypotheses, alternative ideas, or solutions. Lateral thinking solves a problem with procedures far from the rigid standards imposed by the steps of convergent thinking (upper panel) using completely radical new perspectives (lower panel). Associative thinking consists of integrating, merging, and recombining ideas that initially have no connections or are even opposed. This thinking type is essential in synthesis sciences, such as ecology and evolutionary biology.

Box 1. Additional Online Resources to Explore Growth Mindset and Collective Creativity

Fostering a Growth Mindset in Graduate Schools

- PERTS – Project for Education Research that Scales
  An organization that helps educators implement evidence-based strategies, including the growth mindset, to advance educational excellence and equity on a large scale.
  www.perts.net
  www.mindsetkit.org

- Stanford University Advises for a Growth Mindset
  Stanford University VPTL (Office of the Vice Provost for Technology and Learning) provides some tips and resources to imbue a growth mindset in the classroom.
  https://vptl.stanford.edu/growth-mindset

- Fostering Growth Mindset in Grad Students, University of New England
  Some resources on fostering the growth mindset, specifically for graduate students.
  https://online.une.edu/blog/fostering-growth-mindset-grad-students/

- Mindset Works
  Mindset Works is a company providing several (not free) kits to promote the growth mindset. Aimed mainly at schools but with resources that could be useful at other educational levels.
  www.mindsetworks.com/

Collective Creativity – Team Network Interactions and Performance

- Center for Collective Intelligence, Massachusetts Institute of Technology (MIT)
  Its mission is to understand collective intelligence at a deep level to be implemented in different organizations.
  https://cci.mit.edu

- International Center for Studies in Creativity, Buffalo State, The State University of New York
  It was the first university program to teach the science of creativity at a graduate level.
  https://creativity.buffalostate.edu/

- Uri Alon Lab, Theater Lab, Weizmann Institute of Science
  They study basic principles of human interactions with concepts borrowed from improvisation theatre and tools from physics and computer sciences.
  www.weizmann.ac.il/mcb/UriAlon/

- Centre for Collective Intelligence Design
  They explore how human and artificial intelligence can be combined to develop innovative solutions to social challenges.
  www.nesta.org.uk/project/centre-collective-intelligence-design/

excellent example of literature as inspiration. Running multiple projects simultaneously or switching topics can increase ideas connectivity and promote associative thinking. REM (rapid eye movement) sleep also promotes associative thinking [7]. Therefore, to be creative, it is worthwhile to indulge in spending time on other activities, taking walks, or even napping. These activities were part of the daily routine for Darwin and other creative scientists. As the history of science shows, many breakthroughs were made when scientists were distracted or resting.

Facing the Fear to Fail

Students, and scientists as well, usually learn more from their mistakes than from their successes. One of Weinberg's [8] tips for starting a career in science is to jump in without fear of doing research. Today, there are no scholars who know everything about a particular discipline. We must begin to do science by mastering the needed tools along the way, with curiosity as an ally, learning from our mistakes. Students at the beginning of a scientific career usually ask themselves how to know where the frontier of knowledge is. Weinberg [8] advises investigating the literature of the field in search of contradictory results. While Weinberg [8] suggests 'courage' and 'go for the messes – that is where the action is', Alon [9] proposes taking more prudent risks. Alon argues that each phase of the formation (i.e., graduate student, postdoctoral researcher, and senior scientist) requires questions with different degrees of difficulty. Both authors agree that research plans should respond to essential problems while maintaining a broad perspective. To avoid frustration, students have to choose between jumping into the ocean of science or taking prudent risks, depending on their personality.

Collective Creativity

The production of knowledge has evolved from a solo, introspective activity to a collective and social one carried out by research teams of variable size and objectives [10]. Although it is well known that conversations with colleagues and brainstorming sessions are essential for getting novel ideas, solving problems, and increasing our creativity, the collective basis of creativity has barely been explored (Box 1). Creativity emerges from the recombination of ideas connected through a network of minds [11]. Therefore, fostering connections among researchers will improve both individual and group creativity. Woolley *et al.* [12] showed support for the existence of a collective intelligence factor as an emerging property of the interactions among group members. They demonstrated that the ability to solve complex problems was significantly higher when group members worked collectively than when they worked independently. The collective intelligence turned out to be independent of both the average and maximum intelligence of the group members. However, having a team of brilliant people is not enough to make a group intelligent. Collective intelligence correlated significantly with three factors: (i) the mean social sensitivity of group members; (ii) the distribution in the speaking turns of group members; and (iii) the proportion of women in the group [although this factor correlated with factor (i)]. These results suggest that in very hierarchical groups (with a clear alpha male or female dominance and one or two people monopolizing the meetings) the information mostly goes in one (top-down) direction. These groups will show a reduced number of interactions and low collective intelligence. By contrast, in less hierarchical groups, speaking opportunities are balanced, the information goes in all directions (top-down and bottom-up), and there are more interactions among members that nurture collective intelligence. It is encouraging that this collective intelligence can be promoted through communication networks and not only in a face-to-face way [13], which can facilitate work with colleagues from different institutions and generate productive networks both nationally and internationally.

In a more in-depth exploration of the role of diversity on team performance, Woolley *et al.* [14] found that there is a unimodal relationship between diversity in cognitive styles and collective intelligence. Moderately diverse groups presented the maximum values of collective intelligence compared with more homogeneous groups that lack of a variety of perspectives and skills needed to perform well in multiple tasks. By contrast, highly heterogeneous groups might have communication and coordination difficulties. Conversely, AlShebli *et al.* [15] found positive linear relationships between structural diversity variables (i.e., age, race, gender, and affiliation) and team performance. Structural diversity appears to be important, not just for collective intelligence, but also for scientific impact. Diversity, especially ethnic diversity, correlated positively with the impact of scientific articles [15]. The rising trend of knowledge production by teams could be based on the existence of collective intelligence, together with the increasing complexity of scientific problems.

Creativity should be considered a skill to be cultivated throughout our scientific lives, both individually and collectively. As the film director David Lynch advises, negativity is the main enemy to creativity. Our responsibility as scientists and mentors in postgraduate education is to help unleash students' creative potential, reduce their frustrations, and increase their joy of doing science.

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Science & Society

COVID-19, Health, Conservation, and Shared Wellbeing: Details Matter

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Many have stridently recommended banning markets like the one where coronavirus disease 2019 (COVID-19) originally spread. We highlight that millions of people around the world depend on markets for subsistence and the diverse use of animals globally defies uniform bans. We argue that the immediate and fair priority is critical scrutiny of wildlife trade.

Novel COVID-19

Classified as a pandemic by the World Health Organization on 11 March 2020, a marketplace in Wuhan, China has been identified as a hotspot for the early spread, and perhaps origin, of COVID-19 [1]. Since the outbreak began in December 2019, the virus has spread to more than 200 countries with global fatalities presently exceeding 367 000 as of 31 May 2020 (https://www.who.int/emergencies/diseases/novel-coronavirus-2019). Extreme forecasts predicted that >2.7 million people could die of COVID-19 in the US and UK alone (https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-03-16-COVID19-Report-9.pdf). The restrictive measures implemented to limit disease spread have involved evacuated schools and university campuses, cancelled sporting events and public gatherings, broad-scale travel bans, and stay-at-home ordinances. Byproducts of these measures include widespread unemployment, closure of many small and independent businesses, geopolitical discourse about globalization, and an economic recession sweeping the world almost as swiftly as the disease itself. This calamity leaves the world's governments and thought leaders searching for answers. Such answers are urgent not only for human health but also for conservation.

Zoonotic Origins of Many Pandemics

What COVID-19 has made clear is that we have not learned the lessons from past pandemics. Approximately three-quarters of emerging infectious diseases in humans are zoonotic in origin [2]. The COVID-19 outbreak is but one of many pandemics that have been triggered by human–animal interaction (Figure 1). The plagues were likely spread by the *Yersinia pestis* bacterium associated with rats (*Rattus* spp.) and their fleas [3]. Cohabitation with rats killed hundreds of millions of people in these pandemics (Figure 1). Even more directly, many others have been initiated by the handling or consumption of wildlife as meat or medicament, real or imagined (Figure 1). Such pathways of zoonotic disease transmission have been vociferously highlighted as a prime trigger of pandemics [4].

HIV, for instance, which has killed upwards of 35 million people to date, derived from the butchery of wild chimpanzees (*Pan troglodytes*) as meat [5] (Figure 1). The 2009 novel H1N1 influenza virus, which passed from infected pigs to humans at a meat production facility in Mexico [6], killed a (confirmed) minimum of 18 500 people, with the actual toll likely an order of magnitude, or more, higher [7] (Figure 1). Today, several wild animals are candidates for the reservoir of COVID-19 [8]. Although the source species has yet to be formally identified, bats (Order *Chiroptera*) and pangolins (Family *Manidae*) have been implicated as intermediary hosts [9] (Figure 1). Prized for their meat and purported medicinal value, several species of pangolin are now endangered and the marketplaces where they, and countless other species, are traded are prime for zoonotic disease transmission [4]. At one such market in Malaysia, animals were found to be hosts for 19 bacteria, 16 parasites, and 16 viruses that could be passed to people [10]. Thus, even in the absence of pandemics, diseases borne from human–animal interaction in markets can kill people and initiate epidemics [11].

Creating a More Sustainable Future for People and Animals

We recommend that the most immediate and fair priority is critical scrutiny of wildlife trade. First, the criminality of such trade