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Creativity and the brain: An editorial introduction to the special issue on the neuroscience of creativity



The creative ability of the human brain, among the newest products of 3.8 billion years of evolution on Earth, may be humanity's most identity-defining feature in the age of artificial intelligence. Many of the most complex things humans do are now done—or soon will be done—far better by computers. Creativity projects to be the greatest exception. There has never been more widespread recognition that understanding and fostering human creativity is a priority for scientific research. The capacity to generate ideas that are both divergent and useful is widely recognized as valuable for learning and practice in the arts and sciences, and as a driver of the modern innovation economy. This value will only increase in the foreseeable future. Because creativity has such broad and diverse impacts, the neuroscience of creativity is being pursued by a diverse set of researchers. As is generally true in the early stages of a field, research endeavors into creativity neuroscience have often been undertaken separately by researchers siloed within sub-disciplines of psychology, education, industry, and clinical neuroscience. For the neuroscience of creativity to fulfill its considerable potential, it is important to develop greater mutual awareness and cohesion among researchers, and communication with educators and other stakeholders, so that priority directions can be identified and pursued. Meeting this need is a primary objective of the Society for the Neuroscience of Creativity (SfNC). This special issue (SI) on the neuroscience of creativity, guest-edited by a group of us who serve on the SfNC Executive Committee, is aimed at bringing together both expository and new empirical work from creativity neuroscience labs across the globe. We hope that this SI can contribute to (1) mapping the diversity of creativity neuroscience to increase mutual awareness within the field, while increasing awareness of creativity neuroscience across the broader cognitive neuroscience community; and (2) highlighting promising research directions toward stronger coalescence around methods and questions that have potential to catalyze basic understanding of how creativity occurs in the brain and how to enhance it. In this editorial, we attempt to summarize the results and theories reported in this SI, situate them within a larger cognitive neuroscience framework, and provide a modest list of research priorities for the field.

Overview of special issue

This SI attempts to provide a snapshot of current research in the neuroscience of creativity, outlining recent advances in the field. Several studies included in this SI address novel questions related to positive and negative influences on creative performance, including the impacts of stress (Nair et al. 2020) and disease (Paulin et al. 2020;

Gross et al. 2019), as well as influences of mindset (Wang et al. 2019), cognitive reappraisal (Wu et al. 2019), and pharmacological intervention (Baas et al. 2020). The development of the creative brain is explored (Saggar et al. 2019) as are particular attributes of brain morphology and function found in eminent creative achievers (Chrysikou, et al. 2020a; Barrett et al. 2020). Innovative studies examined team creativity using fNIRS hyper-scanning (Mayseless et al., 2019; Lu et al., 2020), and how idea generation takes root in semantic, associative and mnemonic neurocognition (Paulin et al. 2020; Beaty et al. 2020). The neural correlates of musical creativity were investigated along multiple lines (Zioga et al. 2020; Belden et al. 2020; Rosen et al. 2020; Bashwiner et al. 2020). Other studies demonstrated the effective application of methods that have been thus far underutilized in the field, including neurogenetics (Si et al. 2020), network science (Kenett et al., 2020a; Saggar et al. 2019), oculometric signatures (Salvi et al. 2020), 7-Tesla MRI (Schuler et al., 2019), and machine learning (Stevens and Zabelina 2020). Several studies also revealed novel morphometric (Sunavsky and Poppenk 2020; Wertz et al., 2020a; Chrysikou, et al. 2020b; Vartanian et al. 2020), intrinsic (Schuler et al. 2019; Marron et al. 2020), task-evoked (Chen et al. 2019; Wang et al. 2019; Becker et al., 2020; Agnoli et al. 2020; Rominger et al. 2020; Benedek et al. 2020; Hartung et al. 2020; Oh et al. 2020; Roberts et al., 2020; Takeuchi et al., et al. 2020b), and structural connectivity (Wertz et al. 2020b; Takeuchi et al., 2020a) characteristics associated with individual differences in creative thinking, including connectomic analysis of the novel construct of creativity-specific anxiety (Ren et al. 2021).

Three theoretical/review papers (Zhang et al., 2020; Girn et al. 2020; Matheson and Kenett 2020) and one meta-analytically-based proof of concept for neurally-informed ontologies (Kenett et al. 2020b) helped capture how cognitive neuroscience researchers conceive of creativity and how the constructs we use can be mapped onto and constrained by brain function. The review articles address original questions including the role of metacognition and mental states in creativity. The meta-analysis explores the important issue of how best to operationally capture cognitive constructs related to creativity with a set of experimental tasks, leveraging the extant pool of neuroimaging data toward a new method for ontological development that has promise for creativity research and for all fields of cognitive neuroscience.

Many studies employed neuroimaging to examine task-induced brain activity and/or brain connectivity (10 studies employed fMRI; 3 studies used fNIRS), or explore how interindividual differences in creative abilities relate to white and gray matter regional structure ($n = 7$),

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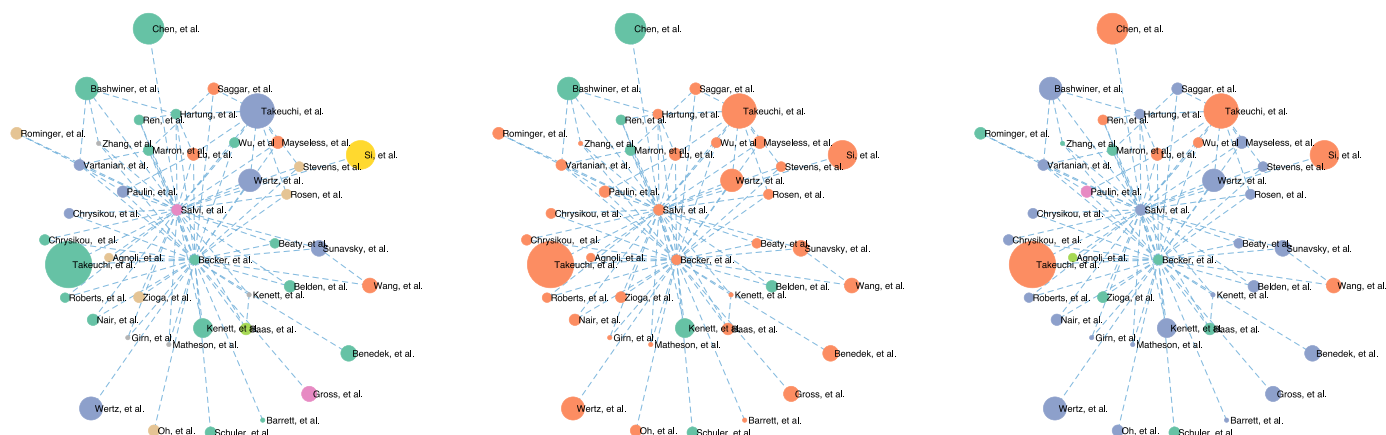


Fig. 1. Summary statistics as a graph for the 42 articles included in this special issue. The graph represents similarity across the included articles. The similarity was assessed by comparing keywords provided by the study authors for each article. Different annotations (node coloring schemes) were used to depict different aspects of each article. The left graph is annotated by the type of neuroimaging modality used, with node coloring as follows: fMRI (dark green), fNIRS (orange), structural (purple), eye-tracking (pink), pharmacological (light green), genetics (yellow), EEG (brown), and review articles (gray). The middle graph is annotated by task-type-intrinsic (at rest) vs. evoked task design, with node coloring as follows: resting-state (dark green) and task-based (orange). Lastly, the right graph is annotated by the continent of the senior author's lab, with node coloring as follows: Europe (dark green), Asia (orange), North America (purple), Australia (pink), and South America (light green). In each graph the size of node represents the number of participants used in each study.

or to measure intrinsic functional connectivity during rest ($n = 7$). Reflective of the field of creativity research more broadly, creative cognition was mainly assessed in the verbal domain (21 studies used only verbal tasks; 5 studies used figural tasks; 4 used a combination of assessments in different domains; and 4 used questionnaires to estimate creative achievements in real life). Creativity assessment was most frequently operationalized via divergent thinking tasks ($n = 21$), among which the Alternative Uses Task was predominant (used in 15 studies). Attempts to better capture the diversity of creative cognition are noteworthy in 4 studies (Baas et al. 2020; Benedek et al. 2020; Chrysikou et al. 2020a; Sunavsky and Poppenk 2020) that used a combination of measures from distinct frameworks (divergent and convergent thinking, creative achievement, openness to experience). In addition, 5 studies (Barrett et al. 2020; Bashwiner et al. 2020; Belden et al. 2020; Rosen et al. 2020; Zioga et al. 2020) represent the substantial and methodologically diverse presence of musical creativity within the field.

To better understand the scope of research covered by this special issue in terms of neuroimaging modality, demographics, and experimental design, we embedded all 42 articles in a low-dimensional space and examined the similarity between them (Fig. 1). To embed each article, we applied Google's Universal Sentence Encoder (Cer et al. 2018) to keywords submitted with each article. The similarity across articles was then assessed using Euclidean distance. The resulting similarity matrix was visualized in a 2-D force layout as a graph, where nodes represent articles and edges represent similarity. We annotated the generated graph using different meta-information: modality used, experimental design, and geographical location of the lab. Fig. 1 left graph illustrates the clear prevalence of fMRI among modalities for exploring brain bases for creativity, followed by structural morphometric, and diffusion-based studies. Largest node-sizes represent consortium-level studies with >1000 participants enrolled. As shown in Fig. 1 middle graph, evoked or task-based studies were most strongly represented within this special issue, compared with examinations of intrinsic or spontaneous correlates of creative thinking. Lastly, Fig. 1 right graph represents geographic location of the labs contributing to the SI (based on senior author affiliations). Labs in North America are most frequently represented in the SI, followed by labs in Asia. Overall, these analyses indicate the breadth and diversity of the selection of articles included in this SI, which reflect our current understanding of the cognitive and neural mechanisms of creative thought.

Outlook and future directions for the neuroscience of creativity

Ten years ago, having a special issue on the neuroscience of creativity in a mainstream neuroimaging journal, with 42 outstanding contributions selected from a much larger set of high-quality submissions, would not have appeared likely. Even just a decade ago, understanding the neural bases of creative thinking was at the outskirts of cognitive neuroscience research. Much has changed since then. A key driver of the movement of creativity neuroscience toward a more central position within cognitive neuroscience has been the commitment of creativity researchers to situate and examine creative thinking within better-established aspects of cognition, such as semantic and autobiographical memory, attention, mentalization, and cognitive control, e.g., (Beaty et al. 2016; Chrysikou 2018; 2019; Kenett et al. 2018; Volle 2018; Zabelina and Andrews-Hanna 2016; Xie et al. 2021; Abraham 2014). Understanding creativity necessitates understanding how these processes take place in the context of creative thinking tasks. On the other hand, creativity is more than the sum of its 'cognitive parts': A comprehensive understanding of how new ideas can come about from already existing knowledge requires a synthesis of extant findings toward a working theoretical framework of creativity neuroscience. Although pieces of this framework are evident across the excellent research featured in this SI, future work toward theoretical unification will be essential. Additionally, questions of the *where*, and—critically—*when* and *how* creativity happens within and between key neural networks, and in conjunction with activity throughout the brain still remain. Are these processes consistent across creative domains? Does the current evidence on task-evoked creativity neuroscience, much of which is featured in this SI, generalize to long-term (e.g., multi-year) creative endeavors? Critically, can creativity be enhanced by enhancing activity in the identified brain systems using non-invasive brain stimulation (e.g., Chrysikou et al. 2013; Green et al. 2017; Lucchiari et al., 2018; Radel et al. 2015) or domain-general training (Saggar et al. 2017)?

The rise of creativity neuroscience research holds strong potential to advance our understanding of more traditional cognitive neuroscience domains. By examining how memory, attention, cognitive control, and social cognition processes, among others, contribute and interact within creative cognition, we can test the validity of well-established knowledge in these subfields. Parallels between creativity research and research examining cognitive and behavioral flexibility are also beginning

to emerge (Uddin, 2021). Creativity neuroscience thus presents a unique testbed for theories across all cognitive neuroscience research. Nevertheless, because fundamental research and methodologies within these domains are advancing rapidly, increased interdisciplinary collaborations among creativity neuroscientists and experts from other cognitive neuroscience domains will be required to advance knowledge.

As evident in the multiple and complementary methods employed in the studies featured in this SI, creativity neuroscience has progressed from simple ‘activation-based’ fMRI studies to complex network analytical paradigms. Much knowledge has been gained from these methods, and cognitive neuroscience methods continue to advance with respect to resolution and multidimensionality. Methodological advances notwithstanding an emerging research gap concerns the relationship between how we study creativity in the lab and how creativity happens in the real world. Although several studies featured in this SI examined aspects of ‘real world’ creativity such as team problem solving (e.g., Mayseless et al., 2020), musical creativity (e.g., Zioga et al. 2020; Belden et al. 2020; Rosen et al. 2020; Bashwiner et al. 2020), and real-life high creative achievers (e.g., Chrysikou et al., 2020a; Chrysikou et al., 2020b), much additional work using ecologically valid, real-world tasks will be required to ensure broad generalizability of creativity neuroscience findings.

For both lab-based and real-world creativity measures, a key future direction for creativity neuroscience is the development of a clearer and more uniform ontology of creativity constructs and measurement. In order for studies to inform each other, researchers must agree on a vocabulary so that the same terms refer to the same constructs and, most importantly, use consistent measurement instruments/tasks to operationalize these constructs. In this SI, (Kenett et al., 2020b) demonstrate proof-of-concept for a novel approach to deriving a neurally-informed ontology of creativity measurement that leverages meta-analytic neuroimaging data in combination with representational similarity analysis. Approaches such as this one that leverage the ever-growing body of creativity neuroimaging data to empirically optimize the fit of tasks to constructs are promising for the future of creativity measurement.

Across these promising directions for future research, creativity neuroscience has substantial opportunity to benefit from, and contribute to, the momentum toward open science that has developed in the broader fields of neuroimaging and cognitive neuroscience (Poldrack and Gorgolewski 2014). To reduce publication bias, preregistering a study plan with details about data acquisition, exclusion criteria, and data analysis before any data have been acquired should be encouraged when practicable (Gorgolewski and Poldrack 2016; Open Science Collaboration 2016). Further, data sharing irrespective of the sample size of the study should also be encouraged. It has been convincingly argued that greater availability of data from small-sample studies could help with failing faster, developing innovative methods, improving statistical power for future studies (Mumford, 2012), as well as validating older results on newer datasets (Saggar and Uddin 2019).

There is no lack of enthusiasm for creativity neuroscience, but the growth of the field depends greatly on how effectively that energy can be harnessed. In these early days, individual studies are not always clearly contextualized in relation to existing studies, and there are instances of crosstalk and redundancy that cloud interpretation and slow progress. Scientific societies play a crucial role in the development of a field by providing platforms for sharing new ideas, establishing standards for methodological rigor, and fostering cohesion and collaboration to achieve a force multiplier-effect. SfNC was formed with the academic charter to support interdisciplinary research on the neural and cognitive bases of creativity and related processes, and to provide an inclusive forum for communicating this research so that it has maximal impacts for education, health, innovation, and artistic performance. SfNC and other organizations focused on the rigorous empirical study of creativity, and projects such as this SI that present the field both to itself and to the broader neuroscientific community, are essential for combining the en-

ergy sources surrounding creativity neuroscience to advance the field in productive directions.

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