HOW CREATIVITY WORKS IN THE BRAIN

Insights from a Santa Fe Institute Working Group,
Cosponsored by the
National Endowment for the Arts

ART WORKS.

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July 2015

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National Endowment for the Arts
arts.gov

National Endowment for the Arts
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The NEA's Office of Research & Analysis would like to thank the following individuals for valuable feedback on the report: Eric Schulze, National Science Foundation; Bruce Carter, Florida International University; and Rex Jung, University of New Mexico.

Library of Congress Cataloging-in-Publication Data
The Nature of Creativity in the Brain (Meeting) (2014 : Santa Fe, N.M.)
How creativity works in the brain : insights from a Santa Fe Institute working group / cosponsored by the National Endowment for the Arts.
pages cm
Includes bibliographical references.
1. Creative ability--Congresses. 2. Creative ability--Physiological aspects--Congresses. I. Santa Fe Institute (Santa Fe, N.M.) sponsoring body. II. National Endowment for the Arts, sponsoring body. III. Title.
BF408.T426 2014
153.3'5--dc23
2015023504

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"Creativity is essential for the arts, for innovation, and for human flourishing. *How Creativity Works in the Brain* makes a compelling case for investing in the interdisciplinary research needed to understand, measure and foster creativity."

—Thomas Kalil, Deputy Director, White House Office of Science and Technology Policy

"As far as I know, *How Creativity Works in the Brain* is the best collection of perspectives about how the brain produces ideas 'out of the box,' one of the principal ingredients of creativity."

—Mihaly Csikszentmihalyi, author of *Creativity: Flow and the Psychology of Discovery and Invention*

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PREFACE

The Nature of Creativity in the Brain

What is the anatomy of an "aha" moment? How and why did we evolve to have such experiences? Can we prime ourselves to have them more often? Why should we care? These and similar questions were the recent focus of a cross-cutting investigation by the National Endowment for the Arts (NEA) in partnership with the Santa Fe Institute (SFI).

SFI routinely brings together experts from various fields to tackle complex research questions with far-reaching consequences for policy-makers and the general public. Questions about "the nature of creativity in the brain" amply merit this type of trans-disciplinary dialogue. The arts and sciences, technological progress, economic prosperity—nearly every significant advance achieved by entire societies—are driven by human creativity. Yet somehow our understanding of how creativity should be defined, nurtured, and optimized remains surprisingly elusive.

This soon may change. A sense of urgency is building around the need to harness and spur creativity to answer a broad range of societal concerns. Creativity and innovation, along with critical thinking, problem-solving, and collaboration, are viewed increasingly as essential for enabling our workforce to better compete in knowledge-based economies. At the same time, hundreds of millions of dollars and more than a billion Euros are pouring into large-scale efforts in the U.S. and in Europe to support medical research and technologies that can improve our understanding and manipulation of the human brain. The time is ripe for creativity research to assist in and benefit from those larger efforts.

It's conceivable that soon we'll be able to see what an "aha" looks like in real time. Or to peer into the swarm of neural activity that occurs just before the lightbulb flashes on. Ultimately we might be able even to understand the physical attributes of memory and watch it construct fresh associations with other knowledge, ideas, or experiences when the next "Eureka!" hits.

Spanning disciplines as varied as cognitive psychology, neurobiology, education, and the arts, the Santa Fe Institute working group explored these possibilities in a two-day meeting. The artists at the table were uniquely situated to describe how creativity looks and feels from the inside. Their insights neither contradicted nor perfectly aligned with the views of other speakers, some of whom considered creativity in terms of novelty and a capacity for problem-solving. For the artists who participated, creativity represented the struggle to communicate or to invent new languages to illuminate new meanings and contexts; for these artists, creativity is fueled by a basic desire to better understand ourselves and our place in the world.

Why do humans feel compelled to pursue artistic endeavors? It depends on whom you ask. An evolutionary biologist might explain that lion cubs find it fun to "play fight" on the savannah, but that this impulse is actually nature's way of helping to foster important skills they'll need in order to thrive as adults. Perhaps something similar is going on with us when we feel compelled to play piano or put on a play. One of the best drama critics of all time wrote that catharsis consists of the ability to bring intellectual clarity to emotional chaos. If Aristotle was correct, then could it be that our impulse to make and engage with art of all types is actually nature's way of helping us to develop the ability to recognize a signal in all the noise—to find patterns in what previously were a series of random dots?

Just imagine what we might accomplish if we really began to understand how creativity works in the brain. We might transform the way we invest in education so as to instill improved problem-solving and critical thinking capacities across all levels of society. We might revamp Artificial Intelligence to confront and solve the world's most wicked problems many times faster and more effectively than we ever could. Or we might be able to explain that the little girl playing jazz licks on the piano is actually building the pattern-recognition and improvisational skills she'll need one day to cure the common cold, build a better burrito, or write a song that will teach the world to sing.

It's true that the pace of these advances can be unsettling. Not everyone wants science or art to solve the various riddles that until now we've been forced to attribute to the ghost in the machine. But as E. B. White once wrote to a man who had lost faith in the human race, "Man's curiosity, his relentlessness, his inventiveness, his ingenuity have led him into deep trouble. We can only hope these same traits will enable him to claw his way out."

Perhaps the fastest and most effective way for us to claw our way out will be via an all-hands-on-deck approach that synthesizes and activates insights across art, science, and the humanities in efforts to solve these riddles. Scientific validation takes time. Art tends to work much quicker and more intuitively, but it lacks the repeatable, quantifiable validity of science. Shakespeare didn't wait for quantitative proof to guide the aim of his verse. He grabbed pen, paper, and poetic license and took a stab at revealing universal truths—then he refined his work until it sounded right. In so doing, he revealed insights into the human condition that continue to resonate to this day, and which science still struggles to explain.

Inside this report you'll get a taste of what can happen when artists and scientists work together to identify problems and solutions that can accelerate our ability to understand complex issues like the nature of creativity in the brain. This, literally, is the stuff that dreams are made of. And until we figure it out, we'll never be able to truly understand the relentlessly curious "piece of work" that is a (hu)man.

And, as any artist, scientist, or trans-disciplinarian worth her salt can attest: we have to know.

Bill O'Brien
Senior Innovation Advisor to the Chairman
National Endowment for the Arts

July 2015

EXECUTIVE SUMMARY

Overview

On July 9-10, 2014, the National Endowment for the Arts (NEA) and the Santa Fe Institute (SFI) cosponsored a meeting titled "The Nature of Creativity in the Brain." Held at SFI in Santa Fe, New Mexico, the meeting engaged a 15-member working group to perform two tasks:

a) evaluate the legacy of creativity research; and

b) explore new knowledge at the intersections of cognitive psychology, neurobiology, learning, complex systems, and the arts.

Collectively representing all these fields, working group members met just as large public-private investments were starting to converge on basic neuroscience research—notably through the White House's Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative. The timing of the Santa Fe inquiry thus gave it a national policy dimension. By understanding the cognitive components of creativity, where they reside in human neurophysiology, and how they might be fostered for all Americans, the public will be poised better to articulate and monitor the importance of creativity research in relation to broader neuroscientific investments.

Below are specific ideas and themes that emerged from the two-day meeting. They are treated more extensively in this executive summary and in the main report itself.

- **The creative process, exemplified by our nation's artists and embodied in the daily lives of people from diverse backgrounds, merits closer study.**
- **Research on how creativity works in the brain has strong potential value for U.S. health and education, the workforce and the economy.**
- **Artists are unambiguously creative in their intentions and activities. They are therefore ideal partners and participants in studies of creativity in the brain.**
- **There need to be more partnerships among neurobiologists and psychologists, artists and educators to identify the conditions, correlates, and causes of creativity.**
- **There needs to be neuroscientific validation of existing tools to assess creativity in individuals. These tests, if effective, can be adopted more widely by our nation's educators, employers, and other decision-makers.**
- **The time for these research investments is now, when new models, techniques, and technologies for studying the brain are still in development.**

Defining and Studying Creativity

Initially, the central challenge for working group members was how to define creativity. The word means different things depending on one's field of expertise or theoretical lens. For example, artists Polly Carl and Doug Aitken described (and have evinced) creativity in their independent efforts to challenge public expectations of novelty in artwork. Meanwhile, creativity researchers in cognitive psychology and neuroscience offered empirical perspectives on concepts such as "novelty" and "value" or "utility." While recognizing its limitations, working group members tentatively agreed that a baseline definition of creativity should account for the "novelty/value" dichotomy. Creative output, they suggested, reveals both novelty and value.

At the start of the meeting, cognitive psychologist Mark Runco of the University of Georgia summarized 30-year trends in the field of psychology-based creativity research. It rapidly became clear to working group members that no single generalizable theory of creativity has yet emerged. For that matter, members questioned whether a uniform theory is even possible—or desirable. As Robert Bilder of UCLA's Tennenbaum Family Center for the Biology of Creativity noted, however, neuroscientific and cognitive-psychology studies in broad populations have managed to isolate some plausible components of creativity. They include *memory*, *divergent thinking*, *convergent thinking*, and *flow*. Further delineation of these components could help define a conceptual path for greater investments in creativity research.

In this vein, participants representing cognitive psychology and neuroscience reported results from innovative research projects that are enabling a more complete understanding of these four components. Following a review of this progress, participants offered ideas for how research on creativity in the brain can be accelerated and applied most effectively in coming years.

Perspectives from Cognitive Psychology and Education

The most dramatic expansion in creativity-related cognitive science research has centered on psychometric assessment. For example, assessment batteries can test for *fluency*, *flexibility*, *originality*, and *elaboration*. Working group members acknowledged that, as children progress through the U.S. school system, they typically have fewer chances to ideate with fluency but many occasions to take standardized tests, which often require convergent thinking. Two presentations explored specific cognitive components of creativity and, in a broader sense, proposed alternative techniques for measuring student engagement with learning, beyond test scores alone.

- Mariale Hardiman of Johns Hopkins University described her memory-centered study of arts-integrated instruction in a Baltimore inner-city school. Her team's research design incorporated dance movement and other techniques in courses such as ecology and astronomy to test the hypothesis that arts-integrated methods would produce better retention of material than would non-arts experiential learning. The team's hypothesis was supported in findings that arts-integrated approaches to science learning helped students at more basic levels of reading and writing proficiency retain more information long-term than students who began with stronger reading and writing skills.
- Ivonne Chand O'Neal, then at the John F. Kennedy Center for the Performing Arts, described Kennedy Center-sponsored studies of creative arts and learning in 16 arts-integrated and 16 matched-control schools in the Washington, DC-area. Her research suggested positive impacts on multiple cognitive components of creativity, in particular the ability to generate a greater number of original ideas, and the enjoyment dimension of *flow* (a concept pioneered by positive psychologist Mihaly Csikszentmihalyi). Students in the arts-integrated classrooms also reported improved self-confidence, class participation, and persistence in problem-solving, relative to the control group.

Perspectives from Neurobiology and Neurotechnology

Other participants showcased results from neuroscientific studies driven by brain-imaging technologies such as Magnetic Resonance Imaging (MRI) and functional MRI (fMRI). As noted by John Stern of UCLA's Geffen School of Medicine, the identification of brain networks through these instruments has "changed our entire concept of cerebral function over the past 10 years or so." Such tools demonstrate that it is virtually impossible for the brain ever to be at rest.

- In this session, Robert Bilder described the evolution of the brain and of brain research. Referring in particular to the cognitive dimension of flow and its role in creativity, Bilder said flow achieves "a clear balance of [the human brain's] stable and flexible regimes. Those states involve high generativity, productivity, flexible memory combination, and the successful inhibition of intrusive habits or fixed ways of thinking, and they enable us to connect more clearly to drive action or perception."

- John Stern, drawing from his clinical and research practice, explored perception as the root of the brain's connectivity and creativity components. Stern described atypical phenomena such as synesthesia and seizures to illustrate the brain's capability to connect disparate materials. He also discussed competition between two mechanisms of consciousness: the self-reflective function of the brain's default-mode network versus the focused networks controlling motor function, language, movement, and vision.
- Justin Sanchez of the U.S. Defense Advanced Research Projects Agency (DARPA) described the development of neural prosthetics and direct interfaces for the brain to restore normal movement or memory, or to restore function after neuropsychiatric illness. Sanchez' presentation provided video examples of mind-machine interfaces conferring greater independence on amputees and other disabled populations. He discussed the possibility of one day using such devices to enhance or extend creativity in humans.
- Charles Limb of the University of California San Francisco (then of the Johns Hopkins University School of Medicine) reviewed the strengths and limitations of brain-imaging technology and how it might be improved as a research tool. Limb showed video of his brain-imaging lab and highlights from the work he has conducted for the last 10 years in exploring creativity as registered by the brain activity of music-makers. Limb has focused on expert improvisational jazz and rap musicians, among other populations, to illuminate their neurological processes.

Working Group Conclusions

Having heard from each other on disciplinary trends in creativity research, working group members discussed how future breakthroughs might be enabled. Bill O'Brien, the NEA's Senior Innovation Advisor to the Chairman, observed that the idea of measuring and optimizing creativity resonates with many different policy imperatives at the national level, yet "it remains an overheated, under-resourced topic." Tension persists in the form of different disciplinary theories and methods for describing and investigating creativity.

Ultimately, members acknowledged the truth in theater director and editor Polly Carl's description of the art of perspective: "To see yourself small on the stage of another story; to see the vast expanse of the world that is not about you, and to see your power to make your life, to make others, or to break them, to tell stories rather than to be pulled by them." Oriented to this mutually respectful philosophy, participants offered two sequential research goals that should be planted at the intersection of the arts, learning, cognitive psychology, and neuroscience.

Research Objective 1

Discover and describe the neurobiological correlates and conditions under which different kinds of creative experiences occur, using a carefully orchestrated, mixed-methods study design. Such a study could be trans-disciplinary in approach and would consist of three phases:

- Extract phenomenological data from first-person subjective narratives of diverse populations engaged in creative activity, to generate categories and hypotheses for psychological and neurobiological testing;
- Correlate the experiences of creative people and their processes with well-validated psychometric instruments; and
- Correlate aspects of the creative experience with brain activity by using the most promising technology for imaging brain states, e.g., fMRI and electroencephalography (EEG).

Attendant Research Questions

- Is the onset of "flow," as a psychological state associated with creativity, linked to a shut-down or relaxation in the pre-frontal cortex (suggesting a relaxation or shut-down of self-consciousness)?
- How do aesthetic processes during arts creation link to the pleasure centers of the dopamine-driven midbrain system?

Research Objective 2

Submit behavioral assessments of creativity to neurobiological testing to validate them further for the purpose of encouraging their widespread use by educators and employers.

Attendant Research Questions

- What psychometric and neurological tests can be used with K-12 students to determine which instructional systems limit the development of specific creative brain functions, and which allow educators to enhance those functions?
- What existing psychometric instruments lend themselves most easily to validation through neurobiological analysis?

The long-term societal benefits of pursuing these research objectives were elucidated by Charles Limb, himself both an artist (a musician) and a neuroscience researcher. "If we have done a good job of understanding this," he said, "we will know the functional neuroanatomy, the neurobiology of creative behaviors that are linked directly to innovation and problem-solving. We should also be able to manipulate those circuits, so we should be able to come up with [interventions] that will make those things better, behavior therapies [and] technologies that are directly linked to improving things we can't affect right now."

CHAPTER ONE: Background and Rationale

To understand the human brain in all its complexity is a newly defined area of focus for federal investments in biomedical and behavioral research. In 2013, the President launched the BRAIN Initiative, a public-private research effort "to give scientists the tools they need to get a dynamic picture of how we think, learn, and remember."[i] In collaboration with private foundations, universities, and corporations, the initiative's lead federal entities include the Defense Advanced Research Projects Agency (DARPA), the National Institutes of Health (NIH), and the National Science Foundation (NSF). NIH recognizes the BRAIN Initiative as an unprecedented opportunity to explore "exactly how the brain enables the human body to record, process, utilize, store, and retrieve vast quantities of information, all at the speed of thought."[ii]

Health, technological, and economic issues of national significance are driving this research trend. On the technology side, researchers want to know how the brain will adapt to such advances as everyday improvements in computing speed, or the ever-proliferating surplus of on-command and unsolicited data. Google's Director of Engineering Ray Kurzweil (author of *The Singularity is Near*, 2005) has predicted that over the next several years, $1,000 of computing power will purchase an intelligence exceeding that of the human brain. Yet myriad human problems remain unsolved. The current Administration counts The BRAIN Initiative among its "Grand Challenges" demanding innovations in science and technology.[iii]

The foremost aim of the BRAIN Initiative is to spur discovery and testing of new treatments and cures for brain disorders such as Alzheimer's disease, Parkinson's disease, traumatic brain injury, post-traumatic stress, and autism. Recognizing that these conditions take an enormous toll on human and economic well-being, the Obama Administration announced, in partnership with universities, corporations, and private foundations, over $300 million in support of the BRAIN Initiative in fiscal year 2015.[iv]

But the importance of the BRAIN Initiative is not limited to medical treatment applications. For that matter, the Administration's 21st-century Grand Challenges are part of a larger vision called Strategy for American Innovation, which invites public-private sector collaborators to confront challenges ranging from national security to job security. Public-private, interdisciplinary collaborations will prove essential to answer such questions as the following: How can we ensure productivity and competitiveness in a global economy? How can a meaningful education be guaranteed to current and future generations? How can children's creativity be developed and optimized to help them understand a complex world and light their own paths forward? How do we prepare them for jobs that have yet to be invented?

Thus, the BRAIN Initiative and other Grand Challenge-inspired projects can generate data with relevance far beyond specific pathologies of the brain. Underlying all these efforts is the quest to map the brain in action and thereby understand the complex links binding neural anatomy, cognition, and human behavior. With that understanding comes greater potential to solve Grand Challenge problems. Indeed, by some definitions, creativity consists of novel and useful approaches toward problem-solving. (Runco & Jaeger, 2012).

Technical advances at the core of neuroscience, along with trends in such diverse fields as the arts, cognitive psychology, and the science of learning, have shown high potential to explain how creativity works in the brain. In recent years, researchers and practitioners in all four domains of knowledge have underscored the role of creativity in improving individual and societal outcomes.

In 2011, for example, a convening of the National Endowment for the Arts (NEA) and the U.S. Department of Health and Human Services showcased evidence that "arts participation and arts education have been linked with positive cognitive, social, and behavioral outcomes in individuals across the lifespan."[v] This event culminated in the formation of an Interagency Task Force on the Arts and Human Development, currently involving 19 federal entities. Once a quarter, the Task Force hosts public webinars to publicize promising research and evidence-based programs. In 2013, those webinars focused on the topic of creativity and human development.[vi]

As part of its Strategic Plan for 2012-2016, moreover, the NEA committed to a five-year research agenda that will investigate the arts' measurable benefits for individuals and communities.[vii] In pursuit of one research strand, the NEA co-sponsored a two-day working group meeting at the Santa Fe Institute (SFI) to evaluate the legacy of creativity research and explore ways to mine new knowledge at the intersections of cognitive psychology, neurobiology, learning, complex systems, and the arts.

Jennifer Dunne, SFI Vice President for Science, described SFI's mission at the meeting's outset: "Our goal is to discover, comprehend, and communicate the common fundamental principles that underlie complex physical, social, biological, and computational systems. Although we are science-focused, we periodically bleed over into the humanities and into the arts."

> "Steve Jobs said, 'Creativity is just connecting things.' We're excited about how connecting these banks of knowledge in this setting may lead to new insights."
>
> —Bill O'Brien, Senior Innovation Advisor to the Chairman, National Endowment for the Arts

The Santa Fe Institute thus presented the ideal staging-ground for a multidisciplinary exploration of creativity. The meeting sponsors sought to rally diverse talents and knowledge domains around two central research questions: How does creativity work in the brain, and how can understanding these mechanisms generate transformative opportunities to nurture and optimize creativity for the public good?

What is Creativity? The Definition Challenge

Artists do art. Typically, they are not consumed with the need to analyze their creative process or engage in debates about the nature of creativity. Defining terms, however, posed the first challenge for the working group. Members tentatively agreed that creativity combines "novelty" with "value" or "utility" for some purpose or problem.

> "I believe creativity is part of what it means to be human. We all have it. Most of us need to fulfill more of it."
>
> —Mark Runco, E. Paul Torrance Professor of Creativity Studies, University of Georgia

Nevertheless, many artists reject the idea that their creativity in any way addresses a *problem*. Doug Aitken, a multidisciplinary artist and technologist, is not of this group. In a studio such as Aitken's, where 8-12 projects are in motion simultaneously each day in multiple media, "the process is synonymous with problem-solving because you set your own obstacles," he said. "You're making your own tools at whatever level—it's a language, it's tools, it's problem-solving, and they're these functional things. The endpoint might be something which is '*de*-material' or has no physical value for our survival, but you're still in the process of making tools."

So much for one half of a baseline definition of creativity—but what about *novelty*? Dunne cautioned that "as a scientist, nothing is truly novel; we're always building on the backs of many different ideas and bodies of work before us." Similarly, the artists who participated in the working group described their strategic efforts to transform the traditional systems and structures that define "novelty" in art, in hopes of improving the way art is experienced and enjoyed.

Polly Carl, theater director at Emerson College, founded HowlRound as an antidote to the cultural norm of theater as "people sitting in boxes at events curated by others."[viii] HowlRound is meant to capture the feel of a public library through online communication platforms and periodic in-person convenings. This approach is consistent with a new, immersive model of theatre, "which is all about the participatory impulse of the audience to create. It's about problem-solving, it's about civic engagement, it's about community dialogue. It's about the artist actually being a member of the conversation. It's really changing the art form," she said.

In the same spirit, Aitken's *Station to Station* project was conceived to challenge the idea that artistic novelty necessitates distance between creators and audiences.[ix] *Station to Station* consisted of 12 train cars travelling from New York City across the U.S., stopping in 9 or 10 different locations. As the train travelled across the country, it functioned as a mobile film studio, a recording studio, and a broadcast tower, enabling everything to be filmed and shared via social media. Each stop involved a different curatorial selection of artists, musicians, and others, creating a "happening." Aitken defined a happening as different art forms converging to create a moment in time that is unpredictable and volatile, and which empowers the viewer to partake in it. *Station to Station* thus collapsed cultural and artistic silos:

> The idea of the gallery being one place, the museum being one place, the venue that the musician plays at over and over, is removed. Then you have a different condition for creativity. I think we see in the contemporary culture, that music is way 'over here,' contemporary art is 'here.' Literature, filmmaking, all these things, they're shrouded in this system that has a set of critics, that has websites or magazines. *Station to Station* is a radical act of cross-pollination. I believe that the future of our culture will be where there's radical friction between these mediums and where people just make what they make the way they want to make it.

According to cognitive psychologist Mark Runco, E. Paul Torrance Professor of Creativity Studies at the University of Georgia, the arts are inherently creative because they exist for the purpose of exploring originality or the attributes of the self. Other participants observed that while artists can be said to *aspire* to creativity as a rule, the novelty of the outcome is not guaranteed—nor always valued. Still, the unambiguously creative *intent* of most artists presents what William Casebeer, a research manager for Lockheed Martin's Human Systems Optimization Laboratory, called a target for neuroscientific researchers. Such researchers might conclude, in Casebeer's words:

> 'Hey, we've identified this *aha* moment . . . Here's what looks like behavior [leading to creativity]. Here's the role that it plays in the ontogeny of the creative process.' And then we can say, 'Okay. Let's find that neural signature, understand its dynamics, and explore its connectivity with these other brain regions that we know are affiliated with behavior.'

In the bioscience of creativity, which encompasses the study of both human and non-human species, concepts such as *novelty* require quantitative definition. "You have to operationalize what you mean by novelty," according to Robert Bilder, director of UCLA's Tennenbaum Center for the Biology of Creativity. In one research project, he explained, "we were looking to see how birds generate novel songs. How do you define *novel*? There, you can use speech sound spectrograms to determine exactly what were the frequency and sequential differences over time, and we can at least quantify it."

Regarding widely-accepted definitions of creativity, Bilder acknowledged that creativity requires "novelty, innovation, disruption on the one hand... but there has to be the imposition of sufficient order to make it of interest, value, or acceptability to the users, whomever they may be." He continued: "Before something goes off into a great deal of unpredictability, more complete disorder, there's some boundary at which you cross into a state that others are not going to appreciate." The results of creativity, he suggested, need to resonate strongly with at least one particular community of practice.

Who Is "Creative?"

Runco examined the enduring popularity of a classification scheme that allows us to place creativity neatly into one of two categories. (Merrotsky, P., 2013). "Big C" refers to eminent-level creativity—the work of famous, unambiguous creators. "Little c" can refer to children's creativity, the creative *potential* that people possess at any age, or to creativity in a domain—"the everyday domain, not a formal domain where creative achievement is widely recognized," as Runco explained. By applying this framework, one can even rank artworks or inventions into corresponding degrees of creativity. "Say Picasso or Freud or Einstein did this many things and sold this many things and these things are cited," Runco proposed. "Just based on the product[s], we're going to go ahead and label them as highly creative."

Creativity literature offers a broader context for the big versus little "c" distinction. Howard Gardner's *Creating Minds* (1993/2011) and Mihaly Csikszentmihalyi's *Creativity: The Psychology of Discovery and Invention* (1996/2013) are among the best known, most in-depth explorations of the lives of highly creative individuals, eminent achievers whose work has enriched the culture or transformed a domain. Gardner's and Csikszentmihalyi's works are premised upon the argument that much can be learned from experts who devote enormous attention and resources to solving problems creatively.

Csikszentmihalyi has argued that attention to eminent creative problem-solvers helps balance the tremendous resources devoted to studies of pathological and dysfunctional states. Moreover, such studies have significance for the general population, in that "if we wish to find out what might be missing from our lives, it makes sense to also study lives that are rich and fulfilling" (1996/2013, p. 11). The big/little "c" distinction also can be viewed as a false dichotomy that obscures the idea of creative potential. As Runco posited, people with Big C once had little "c." Conceivably, to divide these concepts is to shift the research and policy emphasis away from discovery of methods for supporting and encouraging creative potential.

The extent to which a Big C emphasis should drive new investigations of creativity in the brain was not resolved during the working group meeting. Further complicating the idea of classifying creative works and creative people based on their impacts, Bilder reflected that some types of creativity have been deemed valuable only after decades or centuries have elapsed:

> It may be impossible to determine if something is a creative work at the moment; it may become creative at some future point in time. But if you're looking retrospectively, the only way you can do it is to determine if something has value in the moment, and what is *value* varies a lot. Scientific creativity and scientific productivity are often seen as how widely the work is cited. Yet you might think it would be better to judge novelty [by] how much [creative works have] transformed the field. How much has a work created *new* work that has deviated significantly, that is less connected to the body of work that went before?

Gardner's and Csikszentmihalyi's studies were not arts-exclusive; they recognized that common threads run throughout creativity in all fields of human endeavor. Csikszentmihalyi's book included Nobel prize-winners in physics, chemistry, literature, medicine, peace studies, and economics in addition to artists and musicians. Such studies were not undertaken to offer generalizable proof, or even to describe a representative population. Csikszentmihalyi, rather than attempting to "come up with generalizations that hold for all creative persons," aimed instead to "occasionally... disprove certain widespread assumptions" (1996/2013, p.14).

At the meeting, working group members discussed the relative strengths and weaknesses of heuristic versus analytical approaches to study creativity. Charles Limb, a professor in the Department of Otolaryngology-Head and Neck Surgery at the University of California San Francisco, warned: "You cannot get to a general theory by looking at a million anecdotes." Still, working-group members identified qualitative research such as Csikszentmihalyi's as foundational for more generalizable research results.

Cognitive Components of Creativity

Doug Aitken voiced a question on behalf of those who are interested in the origins and processes of creativity but who dwell outside the biological, behavioral, and social sciences. "Why does the study of the brain and creativity have to take place through scientific tests?" he asked. "Why can't it be... an examination of patterns and systems, an understanding of people who are making things?" Charles Limb, who formerly held a dual appointment at Johns Hopkins University School of Medicine and at the university's Peabody Conservatory of Music, offered an answer:

> If you understand not only observations of how creative people actually produce their creativity, as well as how the brain also does it, then you can maybe pull those together and have that precision in order to elicit more creative processes in the future… The brain starts [out] the same, but when it starts engaging a creative behavior, the activity changes in a way that's distinct from when you're not engaged in creativity. To me, that idea has profound implications well beyond music, well beyond art.

There is no general theory of creativity. This is partly because creativity is typically viewed as a *complex* or syndrome that is multifaceted and varied in expression. In defining creativity and determining what to study, both product and process can be described. According to Mark Runco, the creative process may be more important than the tangible result, in part because "what we know about creativity can't be applied in exactly the same way to all domains because they involve very different subjective decisions and processes." The purpose of the Santa Fe working group, therefore, was not to formulate a general theory, which, in Runco's words, would "have to be much more than cognitive. You'd have to have emotion... the happiness, the intrinsic motivation... the *affect*. The creativity complex includes values and attitudes and all of these things that supposedly are important for the creative process. They are influences on it."

Complexity is the essence of the problem for creativity as a topic of research. Robert Bilder explained: "It doesn't have a general biology. It relies on other things that have to do with value and utility that are contextual and societally based." Despite this complexity, a major strand of conversation that developed throughout the two-day meeting was identification of biological components "that are cognitive and that we can have general theories about," as Bilder put it. Some universal cognitive components—contributors to creative achievement—have been isolated through neuroscience and cognitive science across studies of broad populations, occasionally with highly creative groups compared with control groups. They include *memory*, *divergent thinking*, *convergent thinking*, and *flow*.

"Lodging creativity research in the firmament of neuroscience research is one objective of the event."

— Sunil Iyengar, Director, Office of Research & Analysis, National Endowment for the Arts

Working Memory

Creative insight depends in part on new combinations of existing ideas, concepts, and perceptions that have been stored in the brain over time. John Stern, a neurology professor at UCLA's Geffen School of Medicine, observed that memory consists of more than one faculty, and two distinct categories: declarative memory (memory of facts and events) and non-declarative memory (unconscious, procedural memory; knowing how to do things).

Stern explained: "Part of creativity is the brain accessing that non-declarative memory, the learned experience. Humans use preconceived experiences in their creativity, but not always at the level of conscious awareness, as illustrated by how often people experience creative insights when they're doing something else, when they're distracted, when they're not forcing an idea to come." Chris Wood, a neuroscientist and Vice President for Administration of the Santa Fe Institute, expanded on this notion of memory's inherent complexity:

> It's numerous processes, at least two or three. One can disrupt them independently of each other, and yet we still talk about 'remembering something' as if it's the single process of remembering. That may happen with creativity, as well. It may turn out that what we today call creativity isn't one thing, but is one, two, five, seven, nine things. That's progress.

In 2008, the Dana Foundation released study results from a consortium of researchers who independently investigated the arts from the perspective of cognitive neuroscience. A report titled *Learning, Arts, and the Brain* summarized studies showing tight correlations between arts training and improved cognitive capacity and academic performance. Memory was a significant variable in a study linking music rehearsal with memory retention, and in another study linking acting with memory improvement through the learning of skills to manipulate semantic data.[x]

In the same vein, Mariale Hardiman, Vice Dean of Academic Affairs at Johns Hopkins University, where she also directs the School of Education's Neuro-Education Initiative, described a memory-centered study of arts-integrated instruction she led in a Baltimore inner-city school.

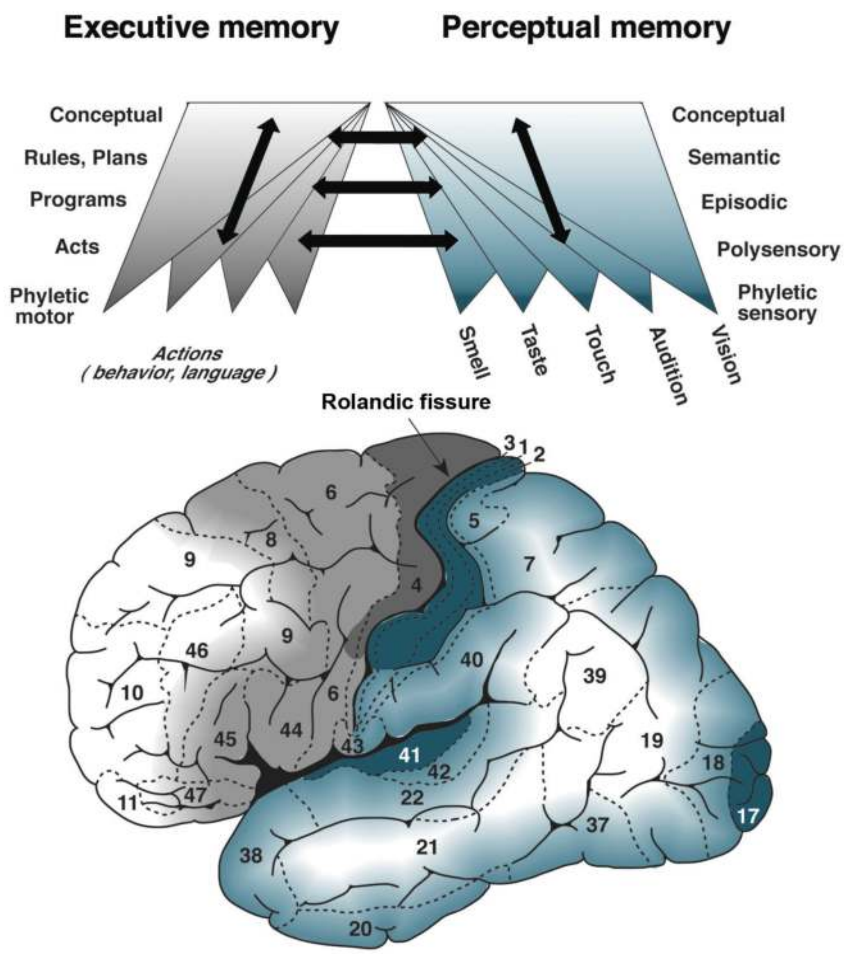
THE BRAIN'S PERCEPTION-ACTION CYCLE

By Robert Bilder

Director, Tennenbaum Family Center for the Biology of Creativity, UCLA

Basically what we've seen over a billion years of evolution is the successive layering of complexity on top of a basic input/output and coupling operation. The evolutionary process does appear to be recapitulated in our own ontogeny; in other words, the development of these brain regions seems to follow a lot of the evolutionary history. There's an incredibly well-organized, topologically succinct connection between every bit of the posterior cortex and every bit of the anterior cortex that honors the levels of processing and the level of evolutionary development within each cortical region. What you get by virtue of those connections between the action-oriented system and the input processing system is a resonant architecture. Indeed… Stephen Grossberg [Founder and Director, Center for Adaptive Systems, Boston University] has developed one of the modern methods for looking at neural architecture. [This is] called Adaptive Resonance Theory, which focuses on the ability of these networks to sustain activation states by virtue of this resonant architecture and the ways in which that resonance can be disrupted to enable new activation states to occur. In short, these are some of the fundamental principles that explain how the brain coordinates input and output to create a unified perception-action cycle.

Figure 1. The Brain's Perception-Action Balancing Act. Adapted from Fuster, 2004.



In a study cohort of 100 students, Hardiman's team sought to determine if the arts, when used as a methodology for teaching ecology and astronomy, would produce better retention of information than would other forms of experiential learning. The study was grounded in a literature review suggesting that 1) memory depends on repetition and 2) certain types of elaboration improve memory. This review of studies in the cognitive sciences and experimental psychology pointed to a range of interventions and effects on memory, but the researchers posited that the arts engage children by repeating academic concepts in a unique way that enhances retention of learning. A summary of Hardiman's study was published in *Mind, Brain, and Education* (Hardiman, Rinne, & Yarmolinskaya, & 2014).

Hardiman's research team, in collaboration with arts-integration specialists and content teachers, developed 5th-grade units in ecology and astronomy for use in an arts-integrated course section and for comparison with a conventional section of the same course.

Each teacher taught one content type through both conditions so that each group of students experienced both pedagogical approaches. Hardiman reported that as an observer, she "went into the control condition when the students were at their desks using worksheets," while in the intervention group "they were holding hands, [as] these kids rarely would be during their school day, to depict how water molecules differed from solid and air molecules." In other examples, students in the control group traced the shapes of galaxies by using pen and paper, whereas in the arts-integrated condition, the students used various dance movements to illustrate the shapes of galaxies.

Post-instruction, no significant differences were found in test results between the intervention and control groups. In follow-up testing, however, a small but statistically significant benefit was observed for the arts-integrated group. Hardiman reported that the biggest difference observed between the intervention group and the control group was for students at basic levels of reading and writing proficiency. Perhaps because arts-integrated approaches to science learning rely less on student reading and writing to demonstrate mastery of content knowledge, students at more basic levels of proficiency retained more information in follow-up tests than did the students who initially showed stronger reading and writing skills.

Divergent Thinking

Memory supplies the brain with sensations and information about experiences of all kinds, along with facts, skills, and emotions we can recognize and recall long after the initial input. Creativity, however, requires more than simple recall. It requires divergent thinking, the ability to associate and combine ingredients, a capacity for which an infinite number of potentially unique recipes may exist.

Divergent thinking has been linked to creativity via a battery of assessments shown to be better predictors of creative achievement than IQ tests and GPA for people in natural environments (Runco, Acar, & Miller, 2010). In tests of divergent thinking, people are presented with an open-ended or ill-defined task, and they have an opportunity to generate possible solutions. Conditions that inhibit and encourage divergent thinking are becoming better known. For example, divergent thinking, and its marker *ideation*, are familiar to most people as brainstorming. However, Runco noted that group brainstorming can occasion more conformity than creativity. Divergent thinking refers largely to fluency, which is not a guarantee of creativity.

Children's divergent thinking—their fluency, originality, and ideational flexibility—can be reliably demonstrated as early as age two. (Bijvoet-Van den Berg, S., & Hoicka, E., 2014). Ironically, as they progress through U.S. school systems, most children will have fewer and fewer opportunities to ideate with fluency but many opportunities to take tests, which tend to require convergent thinking and a single correct or conventional answer. In tests of divergent thinking, by contrast, originality is a good thing.

Runco described work at the opposite end of the fluency spectrum with older adults, "who often suffer from functional fixity. Their thinking becomes very rigid and they tend towards routine." Through John Stern's clinical and scholarly work on brain networks and the brain centers responsible for seizures, he has come to believe that ideational fluency hinges in part on the flexibility of perception. Stern explained:

> If our idea is how we can foster creativity in anyone across the spectrum of people's abilities, the first thing is recognizing that perception is flexible. It's as simple as 'how many ways can you see that,' not 'how many

> things can you do with that.' [Instead,] just look at that, look at it again, and recognize and teach the fact that seeing something is not just seeing it. There's not one way of seeing something for one individual. Seeing something, hearing something, tasting something, it's not set. It's best sometimes to just let go of the idea, sometimes it's best to follow an idea—and not drill yourself into a corner of this is how it has to be.

Runco observed that functional fixity is not an inevitable syndrome that comes with aging. He cited books such as Ellen Langer's *Mindfulness* (1990) and *The Power of Mindful Learning* (1998). These Harvard University-based studies have explored how people of any age can escape the trap of rigid mindsets and move toward greater flexibility and positivity.

> "We have to always think about this as a loop, the perception-action cycle. The cycle occurs about every 300 milliseconds. So three times a second we're going through this process of evaluating our plans, getting inputs, and through this resonance architecture and through mismatch that alters the resonant states, developing new plans for behavior."
>
> —Robert Bilder, Director, Tennenbaum Family Center for the Biology of Creativity, UCLA

Convergent Thinking

Divergent thinking is sometimes discussed as if it were synonymous with (and sufficient for) creativity. In cognitive psychology research, however, one of the most important dimensions of creativity is decision-making, which depends on *convergent thinking*—the ability to think strategically, to apply logic and discretion to narrow a quantity of ideas to the best ideas. Runco noted that a mark of distinction for creative people is that their actions are tactical. For a contrast, he invited the group to consider the creativity of children, who tend to be free of habitual assumption-making and are not as bound by routine and structure as are adults—but who lack discretion.

> They're in a sense more open-minded. But the problem is that they don't have discretion. Kids are already imaginative... they're born that way. We can teach them to constrain themselves. What we really need to do as parents and teachers is to teach them discretion so they know when to do one and when to do the other. We don't want them to lose either of them.

In this context, Martin Storksdieck, director of Oregon State University's Center for Research on Lifelong STEM Learning and a former director of the National Academies' Board on Science Education, discussed the need for non-routine problem-solving. "I think that's where creativity comes in," he said. "When things deviate from the norm and there are unknowns you have to deal with, can you find a solution that you couldn't get out of a playbook, and what does it take to be able to do that? This is one of the '21st-century competencies' people link to innovation and creativity." Similarly, Runco referred to the "aha moments" in creative activity, the last part of a protracted process that involves learning, thinking, and exploring. "That's actually what creativity is," he claimed, "being original but original in an effective manner."

The Brain's "Magic Synthesis"

The free-flowing ideation and the discretion, the divergent and the convergent, work together in what has been called a "magic synthesis" (Arieti, 1976). The magic synthesis in the brain happens when ideas are brought together in a way necessary for creativity. In other words, the brain has to be both divergent and convergent, perhaps at the same time.

It's a process well understood by artists, who often meld together radically different ideas to create a new connection. John Stern proposed a model of creativity in which connectivity can be observed across brain networks that have evolved to a state of intrinsic organization that can be manipulated. Hallucinogenic drug use is one way to disrupt the brain's ability to synthesize, while activities such as reflection and meditation only enhance it. Robert Bilder elaborated that the brain's ability to make connections depends on a mechanism of spreading "brain activation" to unite areas that previously were discrete and independent:

> You can see direct parallels in all kinds of brain-imaging studies of when people have synesthetic experiences, or [are] connecting together two previously disparate ideas. You actually see a brain activation state that encompasses…nodes in what were previously separate graphs and connects them together, so there's actually a direct correspondence between the brain state and the cognitive state. The question is, how can you promote that actively? There's not been much research on how to promote spreading activation in a reasonable and controlled way.

Achieving Flow

The so-called magic synthesis that happens when memory, divergent thinking, and convergent thinking work harmoniously together can be enormously pleasurable, and can contribute to "flow" states. Robert Bilder acknowledged Csikszentmihalyi's foundational work on flow (*Flow: The Psychology of Optimal Experience*, 1990/2008). According to Bilder, flow "involves a clear balance of [the brain's] stable and flexible regimes. And those states involve high generativity, productivity, flexible memory combination, and the successful inhibition of intrusive habits or fixed ways of thinking, and they enable us to connect more clearly to drive action or perception." To understand the anatomy of flow experience, it is necessary to realize that it includes not just the cognitive dimension, but also an emotional one: the ability to achieve enjoyment, sometimes described as a state of ecstasy. Flow happens when someone engages so completely in a challenging activity that nothing matters except the process of accomplishing the goal. Doug Aitken affirmed that in moments of flow, also called being "in the zone," artists make inspired connections and generate creative output.

Flow appears to be characterized by a shutting-down of some normal brain functions and the super-charged activation of others. Using functional magnetic resonance imaging (fMRI) technology, Charles Limb has examined flow states achieved by musicians performing in laboratory control conditions. He reports that when the brain goes into altered states of consciousness such as meditation, dreaming, improvisation, and trance-like states, a phenomenon called *hypofrontality* in the pre-frontal cortex occurs; the usual activity in the pre-frontal cortex shuts down.

Limb has seen this effect in jazz musicians when they improvise. "It is called dissociation," he said. "It sort of implies that there's a shutdown of self-monitoring areas during jazz improvisation or maybe flow states." In other words, musicians are able to suspend the conscious evaluation of their output and simply play. In the brain, Limb argued, "the location of the phenomenon may vary, the robustness of it may vary, the factors that modulate it need to be determined. I think there's something there." Stern elaborated that in a creative process where one is engaged in a task that does not require self-reflective activity, "we end up in a state of productivity that is actually often pleasurable" *because* we're not really aware of ourselves.

But flow is an insufficient indicator of creativity. Bilder pointed out that "in contrast to some of the assertions that you have to be dis-inhibited or uninhibited to be creative," other strong inhibitory controls are necessary for creative achievement. People need to overcome the tendency toward functional fixity explained earlier, to sometimes break habits and rules. According to Bilder, a good question to ask in analyzing brain activity is: To what extent do flow and creativity depend on a turning off, or some kind of active inhibition, of the brain's controlled processing systems?

The Santa Fe Institute working group explored both the biological and cultural implications of flow. Of particular interest to Ivonne Chand O'Neal, former director of Research and Evaluation for the Kennedy Center (now Chief Research Officer of Creative Testing Services), is the *enjoyment* dimension of flow, which she connects with patrons' sense of thrill and surprise, along with overall quality of life and longevity. The Kennedy Center has conducted studies to determine the impact of the arts and arts-integrated learning in school populations in Washington, DC-area schools since 1999.

Chand O'Neal noted that one of the primary findings about the Kennedy Center's Changing Education through the Arts (CETA) program so far is that arts-integrated classrooms have the potential to bring about "deep satisfaction, or the sense of resonance" for children. Echoing Limb and Stern's explanation of flow, Chand O'Neal discussed the pleasure or enjoyment factor inherent in creativity, and its potential to offer freedom from negative self-consciousness and self-critique. She called it "the odd feeling that you belong to this thing, and it belongs to you, that *happiness*."

In her own research, the children in arts-integrated classrooms who felt a sense of belonging showed the greatest number of positive markers for engagement and "grit" (defined as persistence in solving a problem). Chand O'Neal explained that this sense of affiliation to the classroom is nurtured when children believe that their ideas and opinions can be heard, that they feel safe enough in the environment to express themselves.

Her study design included 16 arts-integrated schools and 16 matched-control schools. Students in 4th- and 5th-grade classrooms were chosen for their potential to shed light on a "4th-grade slump" described in research literature as affecting the creativity of 50-60% of U.S. children around the age of nine. (Torrance, 1968). The Kennedy Center-sponsored study involved data collected from 796 students and their parents and teachers over three intervals during one school year. Self-reported data from students indicated the following outcomes, compared with those from classrooms that were not arts-integrated (Chand O'Neal, 2014):

- more positive attitudes about the arts
- greater class participation, including asking questions
- more frequent experiences of being positively challenged
- belief that the arts helped them better understand non-arts subjects, including math and science
- better ability to apply the arts to everyday things
- better resources for solving problems outside the arts domain

Teachers' evaluations included higher overall assessments of students' creativity. As compared with their control-school counterparts, parents of children in arts-integrated schools more often reported evidence of student personality traits associated with creativity, including risk-taking, motivation, and a persistence in solving problems. Chand O'Neal concluded: "They had that flow experience where it was something that was challenging to them, but where the arts made them want to keep sticking with it—that is grit. It was something that kept them constantly seeking out the thrill of solving the problem." Martin Storksdieck made a connection between Chand O'Neal's findings and potential applications to STEM instruction. "If you have data that show that this particular instructional method helps with the lower-performing students and gets the other students to feel better about the science learning," then, Storksdieck said, "you have a winner."

CHAPTER TWO: QUESTIONS OF QUANTIFICATION

How Is Creativity Measured? Current and Potential Approaches through Cognitive Psychology and Neurobiology

The working group aimed to move beyond what is currently known about how creativity happens in the brain. It sought to explore different measurement models for assessing creativity through cognitive psychology and neurobiology. As a first step, it was necessary to review progress already achieved in developing such models.

Cognitive Assessments of Creativity in Individuals

Over the past 30 years, research has been dominated far more by studies of creative *products*, *places*, and *persuasion*—the latter describing an ability to convince gatekeepers of the merit of a creative idea—than by studies of the creative *process* or creative *potential*. (Runco & Kim, 2013). Whereas qualitative work including observational and case studies once led investigation of these areas, published research has trended toward rigorous experimental and quasi-experimental methodologies interpreted through increasingly powerful statistical and analytic techniques, such as structural equation modeling and confirmatory factor analysis.

The most dramatic expansion in creativity research has centered on psychometrics and testing. A comprehensive battery of available assessments includes the Torrance Test (tests for fluency, flexibility, originality, and elaboration) and the Guilford Test (tests for ability to generate alternative uses for common objects).

As editor of the *Creativity Research Journal*, Runco strives to bring greater precision to the word *creative*, using it to specify aspects under investigation, e.g., *creative potential*, *creative performance*, *creative achievement*, or *creative personality*. Throughout the *Creativity Research Journal*, limitations of creativity assessment data are explicitly discussed, as a reminder to readers that tests are samples of behavior—the indicators and predictors of creative potential. For this reason, Runco cautioned that creativity assessments are informative, but not the "end-all." His comment echoed those of other members, who realized that groundbreaking research in creativity is most likely to come when cognitive psychology and neuroscience join forces.

Neurobiological Evaluation and Intervention

Justin Sanchez, who serves as program manager of the Biological Technologies office at the U.S. Defense Advanced Research Projects Agency (DARPA), offered another historical perspective, centering on the immense shift in neuroscientific modes of investigation over time.

The 20th-century version of brain science consisted of static anatomical maps, he explained. According to Sanchez, the lingering legacy of these one-dimensional representations is "one of the things that always drives me up the wall—when I hear about the [federal] Brain Initiative as we know it today, people say 'brain mapping.' I think that's a very old kind of concept. We need to functionalize how the brain is constantly engaging with the environment."

WHAT DOES A CREATIVE ORGANIZATION LOOK LIKE?

By Justin Sanchez

Program Manager, Defense Sciences Office—U.S. Defense Advanced Research Projects Agency (DARPA)

DARPA has this starting point of "anything possible." We don't really have any barriers when we're starting to think about ideas, and I think that this is part of the ingredients for creative interaction. We've heard at [this meeting] about creating friction between mediums, different modes of expression. At DARPA, this could be different disciplines. This could be engineering versus biology versus any number of scientific disciplines.

We have a *culture of disruption*. How can we introduce disruptive technologies that completely change the scope of what somebody is ultimately doing? Part of getting to that disruption is to send program managers to very new environments. In a week, I could be talking to an astronaut who's on a space station. I could be at a creativity workshop, or I could be in a hospital operating room. Again, those environments spark that creative process, and that sense of urgency. We have the urgency to express something or to do something on a very short time scale, and that really pushes us forward.

One of the things that also is really helping us be creative is a *flat organization*, so there aren't a lot of people constraining us in terms of our ideas. There are maybe one or two people that say you can or cannot do this. One way to really get a DARPA program manager riled up is to say something is impossible. Really? *Watch this*.

Again, that really sparks that creative process. The last point here is about focus. We're always trying to drill down to the fundamental details that help push a field or problem forward. I think this also resonates with an artist, either visual or musician. They often try to drill down to those fundamental qualities that move people. I think we have a lot of that at DARPA.

What the agency has produced with these concepts is mind-blowing. The Internet, GPS, we have humanoid robots, we have branching interfaces, self-driving cars; it's truly remarkable. A wonderful group of people that have really put their creativity to use for huge societal and other kinds of issues.

Referring to Bilder's remarks earlier in the symposium (*see sidebar, p.18*), Sanchez suggested a potential priority research direction: "We heard about the brain engaging three times a second with the environment and making some assessments about this perception-action cycle. How are we going to get to that?"

DARPA's Biological Technologies Office is keenly interested in the process of creativity, as well as in neural representations of creativity. William Casebeer, himself a former DARPA project manager and now a research area manager for Lockheed Martin's Human Systems Optimization Laboratory, affirmed that the reason for this focus is that creativity is linked to problem-solving and "all the other things we'd expect soldiers to do."

Sanchez' projects entail the development of neural prosthetics and direct interfaces for the brain to restore movement or memory or to restore function after neuropsychiatric illness *(see sidebar, p. 24)*. Sanchez explained: "We're trying to open up an entirely new area of interfacing with the brain to help us understand these processes a little bit better."

A DARPA project called Revolutionizing Prosthetics aims to restore near-natural arm control to people who have lost upper extremity function due to a spinal cord injury or loss of a limb from amputation. In a video that Sanchez played, a patient with spinal cerebral degeneration, completely paralyzed from the neck down, demonstrated the technology implanted in her brain—using her brain to control a robotic arm. In this case, the technology allowed the patient to feed herself for the first time in many years. In another, an amputee used the prosthetic device to reach up and caress his girlfriend's cheek. These seemingly simple acts served as powerful examples of how mind-machine interfaces can confer greater independence on amputees and other disabled populations.[xi]

In 2014, DARPA announced a project to develop memory prosthetics for the brain. These are "closed-loop devices that can stimulate the brain in order to restore memory function," Sanchez reported. Sanchez noted that throughout the working group meeting, "we [have] heard how important *memory* is in creativity, and concentrated experience … the memory of experience. As we start to fold these two concepts together, I think that we're going to gain additional insight."

Sanchez added that technology is an enabler of leading-edge neuroscience research, primarily through the computing power that can be exploited to examine and explain "the rich set of signals that come out of the brain at such high speed and such high volume." Brain imaging technologies such as MRI, which uses magnetic fields to take pictures of the brain's infrastructure, also play a critical role. The period from the 1990s to 2013 marked an explosion in MRI and functional (fMRI) use, and the world witnessed multiple benefits from those technologies.

Charles Limb concurred that fMRI is a critical component of the "methodological set of tools" of neuroscience. He cautioned, however, that "it's one and only one important resource." Like all the others, it has its strengths and its limitations. "What you're not going to learn from fMRI are the detailed mechanisms at the individual neuronal level that underlie and make possible the functions we're talking about." Where brain imaging is concerned, Sanchez agreed that there is still room to grow. He identified specific opportunities:

> When I say 'room to grow,' I'm talking [not only about] getting down to that single neuron resolution in the brain but multiple single neurons from many different structures of the brain. It's through the aggregation of all of that activity and the descriptive models that can go along with that activity that we can ultimately arrive at the explanation or deeper insight into that creative process. What we're trying to do... is really get into that domain or even just make the technology available [so] that we can start to answer some of those questions.

Sanchez stipulated that underlying all future progress in neuroscientific research technology, the concept of the brain's plasticity and adaptation is paramount. "I don't think of just static experiments that have a start and a finish," he said." I think of the brain constantly engaged with the world and the environment, and developing technologies in order to help understand that, and even engage those processes."

An example of these processes was shown by Charles Limb, who for more than a decade has studied brain mechanisms at work in expert improvisational jazz and rap musicians, among other populations. Through his experiments, Limb has demonstrated that something remarkable is happening neurologically. He detailed his association with one particular rap musician:

> Think about what's going on in his brain to enable him to do that and how different that is from what most of us experience in our normal everyday lives... I tell you, walking around the hospital with some of these freestyle rappers is eye-opening—I should say ear-opening—because they will freestyle everything they see around the hospital into a rhyme non-stop. Seriously, non-stop. It is the most amazing thing.

According to Limb, as improvisers, jazz and rap musicians offer a prime opportunity to understand how the brain produces high volumes of output not only at "a crazy pace," but also at high quality. Limb's experiments have been motivated by the quest to discover how musicians do this and what it means, and thus to study the change in the brain state when people go from memorized activity to spontaneously-improvised performance. Limb has focused on the complex relationship between music and language, two fundamental biological behaviors, "using scientific methods to try to tease them apart [with] art as a tool."

"As a neuroscientist, you have to be exceptionally humble and aware of the pitfalls of your methods, because you don't want to just be storytelling. That doesn't mean that there's anything better available, and so I think the real question is whether or not now is a reasonable time to try to ask some top-down questions using methods that are not quite there yet, and whether or not we'll know more by doing so than we did beforehand."

—Charles Limb, Professor, Department of Otolaryngology-Head and Neck Surgery, University of California San Francisco

Limb shared video recordings of subjects being analyzed under MRI while performing improvisational vs. memorized jazz. He also shared video clips of MRI analyses of the communication between jazz musicians while playing; of a child's improvisation after learning piano scales; and of memorized versus freestyling rap performances.[xii] At the same time, Limb pointed out the limitations of current imaging methods for understanding human creativity. He called it a fundamentally flawed endeavor, but still one worth trying to do properly, even as neuroscientists face pressure to produce spectacular yet easy-to-grasp conclusions from their research. Limb explained:

> It's an article of faith that almost all neuroscientists have, that there is a story to be told at the right level of analysis that explains what perception is, what memory is, what creativity is, but it's not straightforward. That's the problem I see with a lot of measures... You can think of them as data that any correct theory has to be able to explain. But that's a very different role [from] saying you can read off the answers you want from any particular measure.

John Stern, like Sanchez and Limb, combined his clinical and research expertise to share insights he has gained on the components of creativity, the role of *perception* foremost. Returning to the working group's focus on creativity as the generation of novel concepts that have value, Stern argued that before creativity can be sparked from the brain's so-called magic synthesis, the process begins with perception.

To underscore the centrality of perception, Stern shared insights from two sources: studies of seizure patients with psychic aura, the complicated psychological manifestations of seizure that are difficult to describe in language, and studies of people who experience *synesthesias*, two sensory modalities experienced simultaneously.

During synesthesia, people may experience a concept, a number, or a letter as having a color (e.g., "Friday is purple"), or experience an object visually perceived—but not touched—as having weight. A number of eminent musicians and visual artists have described synesthetic experiences, but artists' proneness to synesthesia is up for debate, as is the prevalence of this "rare" condition in the general population (Berman, 1999; Brogaard & Marlow, 2014). Robert Bilder expressed the belief that synesthesia serves as a sort of parable for the brain's connectivity systems, and for an important prerequisite for creativity: the ability to connect two previously disparate ideas. The question, he noted, is how we can promote that function to enhance creativity.

Stern's research illustrates how researchers attempt to mine deep into the brain's recesses to understand how its networks function, using tools such as functional MRI. With fMRI, Stern explained, "you can look across the entire brain, the cerebrum in particular, and identify regions that are active in a given point of time, or [within] a two-second window, and look at clusters...that are active and identify the connections. The idea is that if two regions are active in some type of temporal association, there is a connection between them." The networks that exist within the various regions of the brain have functional relevance; one particular network of interest is called the *default mode network*. It is most obviously present in individuals during experiments when they are not engaged in a task. Normal and abnormal engagement of this network offer researchers important insights into creativity.

According to Stern, the identification of brain networks has "changed our entire concept of cerebral function over the past 10 years or so." These discoveries have demonstrated that, according to Stern, it is virtually impossible for the brain to ever truly be at rest. When participants are told to do nothing in fMRI studies, they naturally will enter a mode of self-reflection. When people are not in this mode, then their motor networks, movement networks, language networks, and visual networks are engaged. "There's a striking jockeying that's present in consciousness between these two assemblies," Stern said. "The networks are continually going back and forth between two consciousnesses."

One important implication is that we can be aware of the external world without interference from our self-perception. As Stern reminded the group, this is how we can achieve pleasurable states of creative productivity. To reinforce the point, Stern offered his experience with people who suffer severe depression; depressed states are characterized by hyper-reactivity and "obsession with self and memory," he said.

As experimental brain research and fMRI peel back successive layers of complexity in the brain's systems, existing theories are either validated or disproved, and new questions arise. They may differ considerably from a researcher's original intent. According to Stern, this is not a problem:

> The very interesting findings are ones that, although it's heresy, we're not looking for. [In] scientific experiment[s] based upon hypothesis-driven inquiry, you take small steps forward. Then when you come across something which is completely unexpected and inexplicable, that's when there's a major step forward, where you have to start designing new experiments to try to tease out what that meant.

To unpack the complexity of understanding creativity through neuroscientific research, Charles Limb proposed that it is necessary to distinguish between two different questions. One is, what is creativity and how does it work? Is it one or many things? Second, how does the brain do it?

Similarly, William Casebeer suggested to the Santa Fe Institute working group that "as we go forward and make concrete proposals, we need to make sure that there's enough flesh [on] the skeleton [so] that we can articulate the nature of the concepts we're working with, that there's not going to be radical disagreement about what they mean, that we have clear hypotheses and bring them out in a testable fashion that leverages this new technology."

Whose Creativity Merits Additional Research?

A dilemma that has beguiled researchers for decades and that provoked lively debate at the symposium is the issue of "Big C" versus "little c." Is there a Big C creative brain, and a brain for the rest of us that is structurally different? If so, does one merit investigation and not the other? Taking in the diversity of opinion and approaches represented at the symposium, Charles Limb remarked that many artists live differently than many scientists, and the rap artists he spends time with live differently than everyone else. Thus, "you have to get into their world, not get them to go to your world." Jennifer Dunne summarized the vexing matter of how to bridge the worlds of arts and science to move creativity research forward:

> One way of characterizing the dilemma is that we've got this top-down process at the high-level, the artistic professionals—high-end creatives—and we are trying to extract patterns from that to characterize generality at the high level. Whereas, coming from the bottom up with neuroscience, what can be done to characterize creativity using techniques such as fMRI? But then there's this big hole in between the top and bottom levels. What is the connection between the lower and higher levels? How do we bring those two scales down and up towards each other?

A so-called "Mad Genius Controversy" has consumed considerable attention in creativity research for decades and has contributed to the belief that creativity is a matter of biological fate rather than a malleable process, and that highly creative people are outliers meriting close examination and dedication of research resources. Mark Runco noted that groundbreaking research in the 1950s at the Institute of Personality Assessment and Research (now the Institute of Personality and Social Research) at the University of California, Berkeley, helped establish this important and enduring focus on mental health and psychopathology.

Albeit in a different way, Robert Bilder's work at UCLA's Tennenbaum Family Center for the Biology of Creativity is also designed to test the hypothesis that Big C creative people are outliers with respect to certain cognitive and brain properties. However, for Bilder and most of the working group members, this perspective represents a null hypothesis, not a professional conviction. (It also forms a research question that Bilder is currently examining with support from the John Templeton Foundation. This research will investigate the brains and cognitive functions of visual artists and scientists whose work is broadly considered exceptional.) In general, working group members agreed that creative individuals have learned a set of techniques and habits that consistently result in greater creativity—but as Bilder put it, "they're using the same stuff."

The debate about "Big C vs. little c" in creativity research ideally will continue to help researchers to understand the kind of brain functions creative people use in the process of doing their work, rather than imply that creativity exists only for a select few. Nevertheless, as Limb explained about his own research laboratory, he has "stacked the deck in my favor by using high-level experts because I needed to see people who are really good at what they do; the environment's not going to be an issue because they're so good at their task." In brain imaging, he suggested, it's important to have a product so that investigators have something tangible to describe.

Why Study Artists?

According to Limb, scientists benefit from art because it enables us to understand comprehensive behavior fundamental to basic innovation, a premise with implications for the overall adaptability of the human species and "how the mind comes up with something new that did not exist the day before." Thus, the working group's deliberations converged on the idea that it is not so much what artists *are* that is of interest to science; it's what they *do*. Drawing from John Dewey, Casebeer proposed a straw-man synthesis,

> a one-sentence theory that attempts to combine what we've talked about with creativity with what we've talked about with artistic expression. It's the idea that art is concentrated experience. And we can talk about what those terms mean in very concrete manifestations. So maybe the experience has a structure, it's concentrated, we take these higher-order structures and pack them into a small space. Well what makes art creative, right, the principal topic of the workshop? It has to be behavior; otherwise it can't be transmitted. Let's assume we have a social backdrop here. It has to be idiosyncratic, otherwise we couldn't acknowledge that there's something innovative and new here, but it has to be ordered. So I think that creative art is *ordered idiosyncratic behavior that concentrates experience*.

Real-world examples of ordered idiosyncratic behavior that concentrates experience were shared by Doug Aitken in video excerpts from *The Source*.[xiii] *The Source* features 26 conversations with makers "who are creating at high levels in radically different mediums—architects, musicians, artists," he explained. When they sat down with Aitken, the makers articulated *how* they ordered *what* idiosyncratic experience. Aitken asked them to recall the very beginning of their creative experiences:

> What is the impetus of the idea? It's not about this building he made and why he chose that aesthetic language, but where did it come from? I think I found that in a musician like [rock musician] Jack White, who references a refinery he grew up near with the repetitive rhythms he hears, which are like the basic chords of the blues. Or it's a sound system of someone who hears planes flying above and actually talks about lying on the floor of his mother's kitchen and listening to the sound of the refrigerator and loving that hum so much that he wanted to grow up and make electronic instruments that make that hum as the bass of all his music.

Aitken's interviews reveal some of the environmental influences on creativity, along with what he calls "the more internal space where these disparate divergent things collide that create language that is uniquely yours. I think there's constantly this interplay between the exterior landscape and the interior landscape and the, at times, friction, and at other times, flow." John Stern's interpretation of Aitken's interviews is that they lend credence to the idea that creativity is *not* fixed, "that creativity in an individual will vary depending on brain states. And if we can affect brain state, in several different ways... that's the overarching concept."

If creativity is malleable, the key implication, according to Bill Casebeer, is that we need to study creative arts because the art-making process offers a unique opportunity for experimentation:

> I can bottle it. I can use my existing methodologies to look at artistic drawing, in an fMRI chamber, or while we're doing crowdsource EEG, or in the context of the creation of art in a clinical setting with a patient who has OCD [obsessive-compulsive disorder] while you happen to have a deep-brain stimulator in place. It might be that the act of creating art is a microcosm of all the other kinds of creative behavior, one that gives us leverage that allows us to apply science to it so that we can understand the whole mechanism.

By "bottling" arts creativity for experimentation, Bilder claimed, researchers will uncover empirical data to build on the existing cognitive statistics and structural/functional imaging parameters—data that will offer a window on both resting brain states and activated functional network states, which in turn will allow us insight into the unique way creative problem-solvers deploy brain networks and properties during creative tasks.

Studying Creativity across Diverse Domains

Polly Carl and Doug Aitken have devoted their careers to eliminating silos that make some arts experiences feel like "elitist, exclusive clubs," Carl said. Robert Bilder noted that silos also guard competing scientific research agendas; eliminating silos is as much a challenge for the sciences as it is for the arts, and a necessary step if meaningful studies of creativity are to be mounted. Achieving true transdisciplinarity was a major goal of the Santa Fe Institute working group. As Bilder explained, "*transdisciplinary* means you've got to be creating a new discipline, not just connecting disciplines and basically letting everybody take some of the money and go back to their lab and do what they wanted to do in the first place. Step one is investigating creativity across disciplines." Charles Limb elaborated: "We should look at mathematicians. There are many, many different kinds of creativity. Athletic creativity, scientific—I think we should look at every form of creative behavior to find universals in the forms that are not genre-specific."

"I always will say that the arts saved my life. The public library was my space of imagination. I spent hours and hours of my time there because we didn't have a lot of books at home. And so I imagined many things in that library. Had it not been for [it]... I wouldn't have known how to imagine where else I might have gone."

— Polly Carl, director and editor of HowlRound Theatre Commons, Emerson College

The need to account for the diverse creative output of experts across disciplines had already been recognized by working group members. A second dynamic emerged as equally important: the passionate engagement in a creative process, regardless of big- or little-"c" classification, and its importance to overall quality of life and cultural and economic vitality. This theme was developed via both personal narratives and research reports.

Reflecting on Aitken's interviews in The Source, Carl expressed the significance of the creative process: "You realize [from] those folks, and I realize this from my work...we have to make or we die, right? So there's survival, and then there's all this potential for engagement and gradations of creativity."

Ivonne Chand O'Neal's work underscores the value of artistic creativity to people who may never become professional artists like Carl and Aitken. To children in an arts-integrated classrooms, according to O'Neal, it can mean a sense of belonging and states of flow in the classroom, which can translate to greater academic engagement and participation, greater persistence through obstacles and challenges, and greater willingness to take intellectual and creative risks.

Neuroscientists are laying groundwork to explain how and why people can connect so powerfully with the arts, even when, as in the case of Polly Carl, they previously had lacked resources and support systems to encourage creative pursuits. Casebeer pointed to the reward-processing centers in the brain, and experiments such as those conducted by Read Montague at the Virginia Tech Carilion Research Institute (Montague & Harvey, 2014)

Martin Storksdieck emphasized how necessary it is for people to find ways to engage with art and that activate those reward-processing systems. With that type of engagement, he conjectured, "people actually have a fighting chance of unleashing that open-endedness that allows them to be creative."

CHAPTER THREE: NEW PATHWAYS AND PROSPECTS

Charting a Research Roadmap

Working-group members acknowledged the formidable progress made by psychologists, neuroscientists, artists, and others in studying and articulating the nature of human creativity over the past few decades. Real challenges persist, however, in funding creativity studies and in designing credible models for evaluation and intervention in the human brain. There are mismatches between interest and support for such research, just as there are methodological pitfalls.

Mismatch between Interest and Support

Bill O'Brien, Senior Innovation Advisor to the Chairman, National Endowment for the Arts, observed that the idea of creativity resonates with many different areas of national interest for authentic reasons that matter to people, yet "it remains an overheated, under-resourced topic." Researchers in the room could all recount experiences where expressed support for creativity research spawned new, and initially promising, transdisciplinary collaborations. Nevertheless, in many of those cases, administrative bureaucracies sprang up as a result, with orthodox business models constraining innovation. Mark Runco quipped that this trajectory almost always has the same endpoint: "Wait a minute—there's no more creativity!" As Limb reflected, public interest in the topic has frequently outpaced the structures and resources devoted to it. John Stern cited risk-aversion as one more natural enemy of creativity. In general, participants agreed that better knowledge of the brain architecture affecting creativity would help funders prioritize cross-disciplinary research investments.

Methodological Pitfalls

Runco noted that the complexity of creativity, with its multiple modes of expression, is sometimes used to justify poor experimentation and inappropriate test selection. In the history of creativity research, tests have too often been chosen for convenience, not because they are the best estimators for specific hypotheses or theoretical models. In addition, studies have tended to explore correlation, not causation. More purposeful, parsimonious use of the creativity assessment battery has led to the successful definition of cognitive dimensions of creativity, especially divergent thinking. This construct and others represent well-validated cognitive paradigms that researchers have vetted over a number of conditions throughout the years.

On the other hand, neuroscientific understanding of the correlates and conditions under which different kinds of creative experiences occur is still lacking; the neuroscientific correlates of divergent thinking, for example, remain virtually unknown. Several review papers summarize brain-imaging studies in creativity, but the conclusion of most of these studies is that the findings so far are inconsistent. There is a palpable lack of shared methodology. Published papers often report one-time experiments that are difficult to replicate.

Despite the complexity of creativity research, several U.S. policy leaders have expressed an interest, mirrored by the governments of many other nations, in understanding how creativity works and how it can more effectively be leveraged for public good. As Justin Sanchez stated, "We have the director of DARPA going on the record saying this is something that we have to do, and we have the European Union saying we should look at this as an opportunity to really frame the appropriate problems, questions, science, and even education."[xiv]

Targeting Two Research Objectives

Limb reflected on what he called an article of faith to which virtually all neuroscientists adhere—namely, there is a story to be told at the right level of analysis that explains such phenomena as perception, memory, and creativity. Indeed, this belief strongly motivated the scientists and artists participating in the Santa Fe Institute working group meeting. Although the two groups often construct very different kinds of narratives, working group members connected with Polly Carl's description of the art of perspective: "To see yourself small on the stage of another story; to see the vast expense of the world that is not about you, and to see your power to make your life, to make others, or to break them, to tell stories rather than to be pulled by them." With this common philosophy prevailing, participants agreed that at least two research objectives should be planted at the intersection of the arts, learning, cognitive science, and neuroscience.

"You can intervene directly in the brain states to try to elicit differences in cognitive outcomes—you know, impacting creativity by impacting the brain. Or you can come up with interventions that are known to have different creative outcomes and see what the neural correlates of that are. So those are at least two different ways to test hypotheses about the links between brain and behavior."

—Robert Bilder, Director, Tennenbaum Family Center for the Biology of Creativity, UCLA

Research Objective 1

Discover and describe the neurobiological correlates and conditions under which different kinds of creative experiences occur, using a carefully orchestrated, mixed-methods study design. Such a study could be trans-disciplinary in approach and would consist of three phases:

- Extract phenomenological data from first-person subjective narratives of diverse populations engaged in creative activity, to generate categories and hypotheses for psychological and neurobiological testing;
- Correlate the experiences of creative people and their processes with well-validated psychometric instruments; and
- Correlate aspects of the creative experience with brain activity by using the most promising technology for imaging brain states, e.g., fMRI and electroencephalography (EEG).

Attendant Research Questions

- Is the onset of "flow," as a psychological state associated with creativity, linked to a shut-down or relaxation in the pre-frontal cortex (suggesting a relaxation or shut-down of self-consciousness)?
- How do aesthetic processes during arts creation link to the pleasure centers of the dopamine-driven midbrain system?

Limitations of Current Understanding

Regarding the state of creativity research, working-group members were able to identify significant similarities in findings that so far have emerged separately from neurobiology and cognitive psychology. As an example of this congruence, Robert Bilder noted that according to both fields of research, "being more flexible in your thinking seems to be associated with greater flexibility of the actual brain activation states." However, a more exact neuroscientific understanding of the correlates and conditions for different kinds of creative experiences—specifically the cognitive elements discussed in Santa Fe—is still lacking. Bilder explained why there is not yet good alignment between neuroscientific and cognitive models:

> They're getting closer in some respects, but the bottom line is that whatever we come up [with] as cognitive models isn't going to reflect exactly the way the brain is doing it. Our current brain models aren't actually representing the activity we're interested in well enough yet, but through the process of cyclical experimentation, we'll begin to refine. What is the nature of the relationship? Right now we have a lot of people

> talking about emergent properties of brain function, but we need to get to the point of being able to specify exactly what's emerging from what, and then to be able to formalize that a little bit. You're looking for what are actually causal links across levels of analysis. That's where there may be information to be gained.

In other words, cognitive models of constructs such as divergent thinking exist, but we currently lack a clear picture of how those constructs connect to brain physiology. "Flow" is yet another creativity component that neuroscientists have attempted to link with specific brain states. Yet these researchers hardly consider the case closed. Given the significance of pleasure in the creative process—as well as theorized reduction of self-consciousness—how might we link creative flow states to deactivations in prefrontal cortex of the brain?

An approach called neurophenomenology (Verela, 1996) is exploring the multi-method frontier, but a number of challenges must be resolved "to connect research in the various fields that study experience in a manner that fully integrates first-person experiential accounts with third-person neuroscientific measurements" (Bockelman, Reinerman-Jones, & Gallagher, 2013).

Proposed Approaches

The Santa Fe working group exemplified a synthesis of artistic and scientific modes of inquiry. Future investigations similarly could meld arts-based perspectives with cognitive and neuroscientific methodologies to shape research questions and study designs around creativity in the brain, the better to develop hypotheses that will withstand rigorous scrutiny from both sides.

Bilder detailed the compatibility of this transdisciplinary outlook with a phased, or "layered" approach that could start with first-hand descriptions of human experience: "What you're talking about is the process. We have to not lose sight of that, of what's really important from the artist's perspective. That's the highest layer. It has the greatest degree of extraction. It's going to be the hardest for us to understand, but if we want to make a neuroscience connection, then we have to in turn say, 'Okay, what are the other layers that are going to connect us down to dirty biology?'"

Stern affirmed: "I think we get the interventions empirically by interviewing people who are highly successful and then spread out from there to people who are not as successful or mature... children, for example...or gather what's re-testable." To these ends, Doug Aitken's interviews from *The Source,* as well as other in-depth interviews with eminent creators (i.e., Mihaly Csikszentmihalyi's study published in *Creativity*, 1996/2013), have been identified as rich databases for the type of qualitative information that can guide knowledge of human creativity at all levels.

Subsequent steps could involve collaborative research by artists, neuroscientists, and cognitive psychologists. Semantic and thematic patterns could be identified using a variety of textual and computer-assisted methods to form unique heuristics and testable hypotheses. This line of inquiry, according to Bilder, will allow researchers to "extract process, then re-communicate it through a neurocognitive lens."

Mihaly Csikszentmihalyi acknowledged the limitations of his 1996 work in the lopsided participation of economists, scientists, and others, compared with artists, many of whom declined the opportunity to interview. While embracing the rich resource inherent in interviews such as Csikszentmihalyi's and Aitken's, the working group veered away from limiting research to Big C, cutting-edge creators. Casebeer helped the working group articulate a more populist approach using "big data" and analytics to help understand, on a large scale, what creativity is like for everyday people. He said: "I can envision lot of experiments where we crowd source understanding creative acts, and then use more readily accessible technologies, like inexpensive EEG, to allow 20,000 or 30,000 people to participate in the process of being creative, and then using that as data."

Approaching the research in phases is proposed so that researchers systematically may match already-identified functional creative states with their precise neurocorrelates. Robert Bilder proposed a visual organization tool:

> The idea is to intersect the possible methods. You could even make a 2 x 2 diagram of the brain states and cognitive states. And you know, you can identify different cognitive states that were associated with creativity and then use those as the way to interrogate brain

> states that are associated with those brain states. Similarly, you can have brain states that you believe are associated with different degrees of creative cognition and then do the validation steps and determine the extent to which they really do afford correspondence.

After the initial descriptive phase, it will be necessary to delve deeper into the brain's systems, so that functional creative correlates can be charted with respect to big brain networks to determine how they can then be studied and controlled. For example, identifying default network changes will become the foundation for locating biomarkers for creativity. Biomarkers can be studied and tested and interventions developed from those findings. The working group generally agreed that meaningful neuroscientific investigations of creativity call for methods of inducing, encouraging, and eliciting it in as reliable a way as Charles Limb's experiments invited improvisation. The ultimate objective would be to develop a class of interventions based on what is learned from this new wave of neuroscience experiments.

Thus, the core idea is relatively simple. Creativity is expressed through connectivity. Different ideas are represented in different parts of the human brain. If researchers can connect those parts, they can see them activate simultaneously. Bilder observed that various brain-graph-theory models can be used as potential resources; and yet, validation studies are only in their infancy. Technologies such as EEG and fMRI have yet to be deployed fully to achieve the multiphase research objective described in this section.

Significance of Triangulating Phenomenological, Psychological, and Neuroscientific Approaches

Objective 1 is fundamentally innovative because, if achieved, it would advance neuroscientific understanding of creativity while respecting the complexity of the phenomenon and each of its multifaceted cognitive components. As Csikszentmihalyi argued using interview evidence from eminent creators in his seminal work, creativity springs from a confluence of individuals; social, cultural, and professional systems; and gatekeepers who make value judgments about creative works. The working group members shared a fundamental commitment to the premise that non-quantifiable phenomena are important and researchable. We cannot afford to exclude the unique detail and rich understanding afforded by first-hand accounts of lived experience. Just as replicable, generalizable results cannot be produced from a thousand stories, so the story of creativity cannot be told with neural images alone.

In essence, the working group members suggested a way to refine the concept of neurophenomenology: divide labor across the three tracks, design an integrated system of checks and balances, and ensure that the three tracks follow the same mental and semantic models. A recent research paper suggests a way forward. The authors of "Methodological Lessons in Neurophenomenology: A Review of a Baseline Study and Recommendations for Research Approaches" write: "The outcome should not only be a productive experimental development collaboration, but also lead to synthesized results, not individualistic pieces in interpreting from each domain's perspective. Instead the results are the whole, or a big chunk of puzzle" (Bockelman, Reinerman-Jones, & Gallagher, 2013, 6).

Research Objective 2

Submit behavioral assessments of creativity to neurobiological testing to validate them further for the purpose of encouraging their widespread use by educators and employers.

Attendant Research Questions

- What psychometric and neurological tests can be used with K-12 students to determine which instructional systems limit the development of specific creative brain functions, and which allow educators to enhance those functions?
- What existing psychometric instruments lend themselves most easily to validation through neurobiological analysis?

Limitations of Current Understanding

Despite the availability of useful and well-validated psychometrics, one could argue as Runco suggested that without neuroscientific validation, the study of creativity is seriously compromised. Instead, the current focus is on indicators and predictors: "We're talking about how it's expressed," Runco said. "We're not landing on the moon and picking up a moon-rock and saying we understand the composition of this rock; we're *flying by*, like they do with the meteors. We're collecting useful information."

The limitations of psychometrics as a stand-alone methodology has real-world consequences. We need a better knowledge base to determine the metrics by which educators can judge whether they need to intervene in individual cases by refocusing attention, or by broadening attention. Similarly, research along these lines can enable people to learn how to manipulate their own cognitive states to become more focused or more open. Finally, biologically validated tools that assess creativity could not fail to hold value for our nation's employers and for economic growth and productivity at large.

Proposed Approaches

Education is among the most promising fields for applying this proposed research. Instructional interventions could lead to groundbreaking insight into specific ways the arts, and artistic processes, help people develop and retain creative thinking and problem-solving. If children truly experience a 4th-grade slump, then more research is needed to distinguish its correlates and causes—to distinguish between, on the one hand, cultural conditioning within school cultures and, on the other, innate developmental processes taking their course. As a society, we need to determine the best means for measuring such phenomena.

Once brain changes are identified through biological measures and linked to behavioral measures, we will have a better guarantee of good measures. Once it is established that existing cognitive measures commonly connected to school populations can be validated through neuroscientific approaches, the biological measures will no longer be needed because the behavioral assessments will be deemed sufficient.

Neuroscientific Validation of Cognitive Assessments: Significance to Education

For all the talk of the human brain's capacity to make the "magic synthesis," the working group members collectively made a persuasive case that school systems too often are ill-equipped to nurture it. Mariale Hardiman expressed the great promise of the proposed approach to bridge the processes of creative thinking and problem-solving, "because in education it should not be either/or. It has to be both and they have to be married together, and they're not now."

Martin Storksdieck voiced the fundamental logic behind the working group's focus on educational applications and practical implications.

> We can validate tests we already use for students so that we make sure we don't do harm in our instruction. We can test so that the strategies we use aren't limiting some components of the child that we actually cherish... like the development of the more creative kind of self. Or we can test instructional strategies that are deliberately enhancing them. So [in] that sense it is an important component of improving instructional strategy, whether it's a technology-based instructional strategy for gaming, or whether it is one in the classroom or whether it's one outside of the classroom.

In Conclusion

The working group's conversations were infused with a conviction grounded in empirical evidence: creativity is part of what it means to be human. Therefore, every sector of human experience can benefit from intensive, interdisciplinary efforts to identify the granular components of creativity, and commonalities from the everyday to the eminent. The convening highlighted through personal narrative and empirical reporting the problem of creative potential unrecognized for individuals and squandered within institutions, along with what we know right now about settings that support creativity. Parents, teachers, hiring managers, and policymakers who tolerate and even celebrate creativity must be prepared to nurture this resource. Beyond that obvious fact, more rigorous and consistent means of identifying what to avoid and what to do are urgently needed.

There is abundant national interest in so-called creative economies and the distribution of creativity in communities, cities, and countries. How students are engaged, how the creative class is defined, and who can access creativity and thrive from it are all questions with profound practical implications for schools, government, and industry. Moreover, as the participating neuroscientists so vividly illustrated, creativity has implications for human health and well-being as fundamental as the ability to move a limb or recall information. Charles Limb summarized the possibilities:

> If we have done a good job of understanding this, we will know the functional neuroanatomy, the neurobiology of creative behaviors that are linked directly to innovation and problem-solving. We should also be able to manipulate those circuits, so we should be able to come up with [interventions] that will make those things better, behavior therapies [and] technologies that are directly linked to improving things that we can't affect right now.

ENDNOTES

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APPENDIX: PARTICIPANT BIOGRAPHIES

"The Nature of Creativity in the Brain," a Working Group Meeting Cosponsored by the National Endowment for the Arts and the Santa Fe Institute: July 9-10, 2014

Organizers

Bill O'Brien. Senior Innovation Advisor to the Chairman—National Endowment for the Arts.
O'Brien serves as the agency's lead on an interagency working group investigating coordinated investments at the intersection of art, science and humanities, and in a partnership with the Department of Defense to advance research on the impact of creative arts interventions for patients confronting war-related Post Traumatic Stress and Traumatic Brain Injuries. He was an ensemble cast member of NBC's *The West Wing* and has produced plays that have won multiple awards, including the Tony Honor for Excellence in the Theatre for the Broadway Deaf West Theatre Production of *Big River*.

Sunil Iyengar. Director, Office of Research & Analysis—National Endowment for the Arts.
During Iyengar's time at NEA, the office has created an arts system map and long-term research agenda, and has launched a research grants program. Iyengar also chairs the Interagency Task Force on the Arts and Human Development. Some of the NEA's most recent research includes *Valuing the Art of Industrial Design* (2013), *The Arts and Achievement in At-Risk Youth* (2012), *An Average Day in the Arts* (2012), and *The Arts and Human Development* (2011). Sunil and his team have partnered with organizations such as the Brookings Institution, the National Academy of Sciences, the U.S. Bureau of Economic Analysis, and the National Institutes to Health to study the arts in relation to such topics as economic development and the health and well-being of older adults.

Jennifer Dunne, PhD. Professor, Vice President for Science—Santa Fe Institute.
Dunne's research interests include analysis, modeling, and theory related to the organization, dynamics, and function of ecosystems. Much of this work focuses on ecological networks, in particular food webs, which specify the complex feeding interactions among species in a given habitat. In addition to basic research, Jennifer and her collaborators develop ecoinformatic technologies to facilitate sharing, synthesis, visualization, analysis, and modeling of data related to biocomplexity research. Among other editorial roles, she is on the advisory board of the new science and culture magazine *Nautilus*. *Nautilus* publishes about big-picture science by reporting on a single monthly topic from multiple perspectives)

Invited Participants

Doug Aitken. Multidisciplinary Artist/Technologist.
Aitken's body of work ranges from photography, print media, sculpture, and architectural interventions, to narrative films, sound, single and multi-channel video works, installations, and live performance. He recently created "The Source," a series of filmed conversations about creativity in the 21st century. The piece features four-minute interviews with dozens of artists, musicians, writers and thinkers about their creative processes.

Robert Bilder, PhD. Director, Tennenbaum Family Center for the Biology of Creativity; Professor of Psychiatry and Biobehavioral Sciences, David Geffen School of Medicine at UCLA and Professor of Psychology, UCLA College of Letters and Science.
Bilder is a clinical neuropsychologist who has been actively engaged for over 20 years in research on the neuroanatomic and neuropsychological bases of major mental illnesses. He has received many awards for his research contributions, served on diverse federal and international advisory boards, provided editorial service to many scholarly journals, and received multiple grants from the NIH, private foundations, and industry. His work has been presented in more than 100 publications and 300 scientific presentations.

Polly Carl, PhD. Director and Editor at HowlRound: A Center for the Theatre Commons—Emerson College.
Carl's work at HowlRound is focused on promoting practices for 21st Century theatre making based on the core principle that theatre is for everyone. She is also part of the ArtsEmerson programming team at Emerson College and is developing new works for the stage in that context. Over fifteen years in professional theatre, Carl has focused on developing and producing new plays, working with dozens of playwrights and theatre companies from around the country. She spent two years as Director of Artistic Development at Steppenwolf Theatre and served eleven years at the Playwrights' Center in Minneapolis seven as Producing Artistic Director. Her Ph.D. in Comparative Studies in Discourse and Society is from the University of Minnesota.

William Casebeer. PhD. Research Manager for the Human Systems Optimization Laboratory, Lockheed Martin
Many of Casebeer's research interests lie at the intersection of cognitive science and national security policy. His previous work at DARPA included the Narrative Networks and Strategic Social Interaction Modules programs. A former deputy head of the Joint Warfare Analysis Center's Technology Advancement Department, Casebeer authored the book *Natural Ethics Facts: Evolution, Connectionism, and Moral Cognition*.

Mariale Hardiman, EdD. School of Education/Director of the Neuro-Education Initiative—Johns Hopkins University.
Hardiman presents nationally and internationally on topics related to the intersection of research in the neuro- and cognitive sciences with effective teaching strategies, including meaningful integration of the arts. Her research and publications focus on enhancing educational practices through techniques that foster innovation and creative problem-solving for all students. Presentations focus on the instructional framework that she developed, The Brain-Targeted Teaching Model, described in her latest book, *Brain-Targeted Teaching for 21st Century Schools* (Corwin Press, 2012).

Charles Limb, MD. Francis A. Sooy Professor of Otolaryngology-Head and Neck Surgery and Chief of Otology/Neurotology and Skull Base Surgery, University of California San Francisco.
In early 2015, Limb joined UCSF, where he also is director of the Douglas Grant Cochlear Implant Center and holds a joint appointment in the Department of Neurosurgery. He formerly was Associate Professor of Otolaryngology – Head and Neck Surgery and a Faculty Member at the Peabody Conservatory of Music and School of Education at Johns Hopkins University. As a National Institutes of Health postdoctoral fellow, he investigated the neural mechanisms of musical improvisation and the production and perception of music through functional neuroimaging. Limb, who also plays sax, piano, and bass, gave a TED talk titled "Your Brain on Creativity."

Ivonne Chand O'Neal, PhD. Chief Research Officer—Creative Testing Services
O'Neal is a researcher who has studied creativity and the arts for over 25 years. She formerly was the director of Research and Evaluation at the John F. Kennedy Center for the Performing Arts. Her expertise centers on four main topics: artists and their creative processes, how artists conceive their art, how they are influenced, and how their work influences others on an individual, cultural and societal level. Previously, she served as Co-Investigator and Research Director at the UCLA David Geffen School of Medicine where she conducted studies of creativity, as Curator at the Museum of Creativity, and as Creativity Consultant with Disney Channel, NBC, and TNBC.

Mark A. Runco, PhD. E. Paul Torrance Professor of Creativity Studies—University of Georgia, Athens.
Runco was Director of the Torrance Creativity Center from 2008-2010. He has been Editor of the *Creativity Research Journal* since 1989 and is a Past President of Division 10 (Psychology, Art, Creativity, and Aesthetics) of the American Psychological Association. He co-edited two editions of the *Encyclopedia of Creativity* (1999, 2011). Runco's new book, *The New Science of Creativity*, is due out in 2015 along with the first issue of his new periodical, *Journal of Genius and Eminence*. He is President of Creativity Testing Services, LLC (creativitytestingservices.com), which is the publisher of the extensive "rCAB" (Runco Creativity Assessment Battery).

Justin Sanchez, PhD. Program Manager, Defense Sciences Office—U.S. Defense Advanced Research Projects Agency (DARPA).
As a program manager within the Defense Sciences Office at the U.S. Defense Advanced Research Projects Agency (DARPA), Sanchez oversees development of neurotechnologies to revolutionize prosthetics and to enable stress resistance. Formerly an associate professor of Biomedical Engineering and Neuroscience at the University of Miami, he led development of neurotechnologies for treating stroke and paralysis and for deep brain stimulation for movement disorders. His research experience includes use of in vivo electrophysiology for brain-machine interface design in animals and humans.

John Stern, MD. Professor, Department of Neurology, Geffen School of Medicine; Director, Department of Neurology, Epilepsy Clinical Program; Co-Director, Medical Center, Seizure Disorder Center— UCLA.
Stern's clinical activities include utilization of brain mapping techniques to identify seizure-generating regions. His research focus is on the brain networks responsible for the manifestations of seizures, with an emphasis on the impact of these networks on perception and awareness. This research employs functional magnetic resonance imaging (fMRI) to characterize the integration of brain activity. He has lectured and published extensively, authored the book *Atlas of EEG Patterns*, and co-edited the book *Atlas of Video-EEG Monitoring*.

Martin Storksdieck, PhD. Director of Oregon State University's Center for Research on Lifelong STEM Learning.
Storksdieck, former Director of the Board on Science Education for the National Research Council, has overseen studies addressing a wide range of issues related to science education including climate change education, science learning from games and simulations, design of a conceptual framework for new science education standards, and discipline-based education research. His prior research focused on what and how we learn when we do so voluntarily, and how learning is connected to our behaviors, identities, and beliefs.

Chris Wood, PhD. Vice President for Administration, Santa Fe Institute.
Following a faculty position in Psychology, Neurology, and Neurosurgery at Yale. Wood leads the Biophysics Group at Los Alamos National Laboratory (LANL), a position to be held until becoming the Santa Fe Institute's Vice President in 2005. At LANL, Wood's group was responsible for a wide range of biophysical and physical research, including protein crystallography, quantum information, and human brain imaging. Wood also served as interim director of the National Foundation for Functional Brain Imaging for 2000-01. His research interests include imaging and modeling the human brain, computational neuroscience, and biological computation.

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