What are the Neural Correlates of Consciousness?

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Human consciousness is marked by creativity—an element so essential to the human experience that the field which studies many of its products is referred to as "the humanities." However, even the broad field of humanities fails to include all the forms of creativity beneath its wings. While creativity includes artistic forms such as literature, music, painting, and sculpting, it transcends the boundaries of art, penetrating the fields of science, architecture, engineering, and many forms of problem-solving. The extent to which humans have shaped the world around them is an ode to just how far-reaching creativity is. The computer this paper was first viewed on, the printer that will transfer it to paper, the invention of paper itself, the building this paper is being read in—these are all products of creativity. Creativity can be used to describe a product, but it can also describe a person or a process. As such, prior to investigating what gives rise to this creativity, it is important to establish some understanding of what this elusive concept really is.

What is Creativity?

Above all else, creativity is an experience. Although the judgement of creativity might differ from one person to the next, most people can agree to an extent about what is creative or even who is creative. Creativity is defined as "the ability to transcend traditional ideas, rules, patterns, relationships, or the like, and to create meaningful new ideas, forms, methods, interpretations, etc.; originality, progressiveness, or imagination" ("Creativity [Def. 2]," n.d.). Notably, this definition and many others emphasize to important qualities which mark creativity: originality and meaningfulness/usefulness/value. These two properties of creativity define the experience thereof and help to create a boundary within which science can explore creativity. In this respect, several models have been proposed.

The Classical Model of Creativity

The classical model of creative problem solving originates in 1926, after which it has continued to develop into its current form (Aldous, 2007, p. 177). In this model, creativity can be broken down into four phases: preparation, incubation, illumination, and verification (Aldous, 2007, p. 177). The preparation phase is marked by identifying the issue at hand, collecting information, and beginning to ponder consciously (Aldous, 2007, p. 177). Aldous (2007, p. 177) describes that this phase may lead to a solution in the case of simple problems, but for more substantial predicaments one often temporarily abandons the project for the second period, called the incubation phase. The length of this phase may vary, but it is marked by unconscious thoughts and connections relating to the problem present at the back of one's mind. When the unconscious mind reaches a solution and passes it on to consciousness, Carol Aldous (2007, p. 177) calls this the "aha" experience or "a moment of insight" which identifies the illumination phase; this idea is then tested and refined in the verification phase. It is important to notice that only the first and final phase must be conscious within this model. Additionally, one may progress through this model in several ways, returning to previous steps more than once before finally producing a viable solution. The progression between phases, conscious and unconscious, was explored by Melvin Shaw (see Figure 1) (Aldous, 2007, p.177-178).

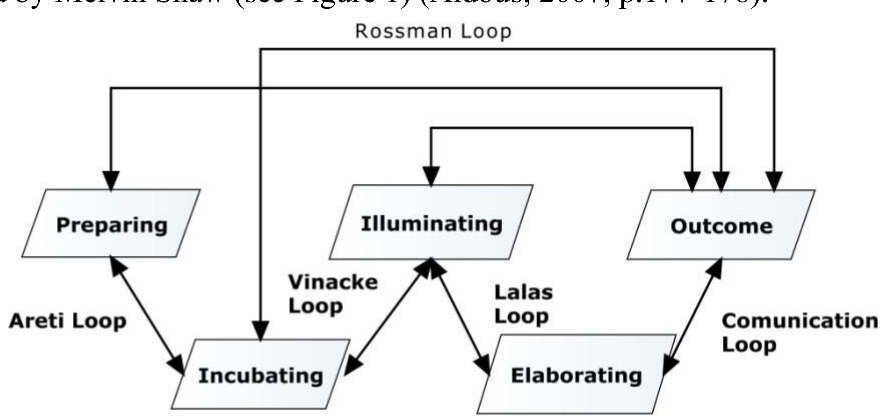

Figure 1. The classical model of creative problem solving, including Shaw's feedback loops (Aldous, 2007, p. 178).

Alternative Model of Creativity

More recently, Arne Dietrich has postulated a separate model. While this model does not operate in the same realm as (nor necessarily refute) the aforementioned classical model, it provides a different perspective on the topic which is valuable for understanding the variability of creativity. Dietrich (2004, p. 1015) classifies creativity into four separate domains, each an intersection of a specific processing mode (deliberate or spontaneous) and a specific knowledge domain (emotional or cognitive) making the use of different neural circuits (see Figure 2).

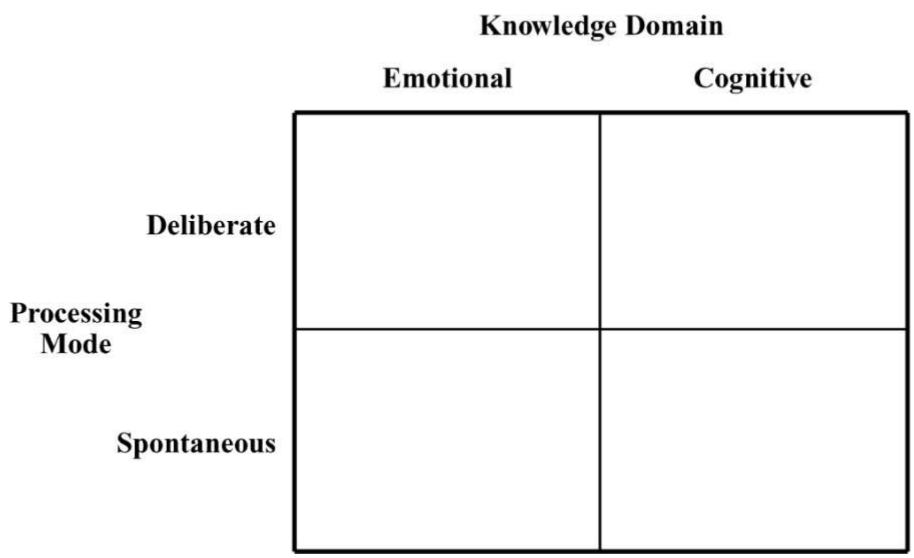

Figure 2. Dietrich (2004, p. 1018) proposes four basic forms of creativity.

Within this model, the prefrontal cortex is an essential operator involved at the end of each of the four paths. Following the creation of a creative idea, the prefrontal cortex serves to bring this idea to working memory, making it conscious, to be evaluated and to incorporate other higher cognitive functions by which novel combinations of information may be converted to a creative manifestation (Dietrich, 2004, p. 1015).

Prior to this final stage at the prefrontal cortex, Dietrich's model is particularly valuable because it helps to address and distinguish the conscious and unconscious processes which underly creativity. Different schools of thought tend to claim that creativity is either a conscious process or unconscious process. The unconscious brain seems to operate in parallel, without working memory's constraints of maintaining and attending to a limited number of objects, allowing for more novel combinations of information, whereas the involvement of the consciousness leads to more deliberate searches that tend to conform to one's own values (Dietrich, 2004, p. 1016-1017). The truth is likely more complex, involving both conscious and unconscious aspects in varying proportions depending on the individual and specific circumstance. As such, Dietrich's model allows for the possibility that any act of creativity can result from a combination of the four types (Dietrich, 2004, p. 1015).

Deliberate Mode—Cognitive Structures

Being that deliberate processing is conscious, Dietrich (2004, p. 1018) suggests that this case is started by the prefrontal cortex which recruits the frontal attention network to search for relevant information in the posterior cortices, the temporal, occipital, and parietal lobes (collectively referred to as TOP). Activation of TOP areas allows for other higher-level functions to act on the same information being processed; the hippocampus is likely involved due to its role in declarative memory (Dietrich, 2004, p. 1019). This form of creativity would be likely implicated in a task similar to designing a scientific research project, solving an organic chemistry problem, or performing a mathematical proof. In all of these cases, the problem-solving is almost completely volitional and the ability to be creative is to a large extent reliant on one's own knowledge.

Deliberate Mode—Emotional Structures

Once again, due to the conscious/deliberate quality of this pathway, the prefrontal cortex initiates the searching, this time retrieving information from the amygdala and other portions of the limbic system for basic emotions, as well as the cingulate cortex and ventromedial prefrontal cortex (VMPFC) for more nuanced emotions (Dietrich, 2004, p. 1019). This process would likely require involvement of the dorsolateral prefrontal cortex specifically due to its role in long-term memory retrieval as well as attention (Dietrich, 2004, p. 1016). As such, the feasibility of this pathway would likely depend on the emotion in question since many limbic structures lack a connection to the DLPFC and, despite projecting widely to the VMPFC, maintain a very limited number of neurons receiving signals from the VMPFC (Dietrich, 2004, p. 1019). This may be viewed as a flaw within this model, suggesting difficulty in involving basic emotions within the creative process, but it is important to realize that these limitations do not translate to more complex emotions. In fact, it might be evolutionary more advantageous to prevent basic emotions processed by the amygdala from leading to creative thought and wide-associations when taking into account its role in fear response and emotions relating largely to survival. When in danger, it is perhaps more useful to focus one's attention on a quick fight-or-flight response rather than assess a diverse array of options. Fittingly, Dietrich (2004, p. 1019) suggests this mode may be involved in realizations acquired during psychotherapy, where a person is purposefully sorting out his or her complex emotional state.

Spontaneous Mode—Cognitive Structures

Moving on to spontaneous processing, the prefrontal cortex is no longer involved at the first stage of creativity. Rather, the basal ganglia, implicated in implicit learning and automatic behaviors, is likely responsible for initiating the unconscious searching within the TOP areas in the case of cognitive structures (Dietrich, 2004, p. 1019). The creative associations made implicitly may then be called into consciousness spontaneously through DLPFC activation, which has been shown to increase during unexpected contradictions to learned association, likely lowering the threshold for said objects to reach working memory (Dietrich, 2004, p. 1019). This form of creativity aligns with the idea of incubation posited in the classical model—it is most similar to the kind of problem-solving which results in a eureka moment. Once again, because of its involvement with existing memories, one's existing knowledge base serves as an enabler or limiter to how good the ideas produced can be. While many of the most brilliant scientific discoveries are said to have been stumbled on by this method, it would be shortsighted to describe it as luck since the pre-existing knowledge base served to make the discovery possible in the first place.

Spontaneous Mode—Emotional Structures

Finally, spontaneous processing in emotional structures is likely to involve the basal ganglia unconsciously searching through the emotions expressed throughout the limbic system, the cingulate cortex, and the VMPFC as the aforementioned discussion would suggest. Intense emotional experiences are likely to create an urge for creative expression because signals involved in emotions, often very important biological markers, are made to be particularly noticeable, beating competing neural groups to reach consciousness and often dominating one's "head-space" (Dietrich, 2004, pp. 1019–1020). This particular creative path seems to be most aligned with the idea of a revelatory epiphany or divine intervention, the mystical possession of an artist which inspires him or her to create a particularly meaningful form of expression.

Proposed Model of Creativity

While the classical model as well as Dietrich's thought-out proposition are both incredibly viable in their own right, they both include their own issues. The classical model seems to make logical sense, but it lacks much scientific backing or neural explanation. It is more of a theoretical outline based on the common experience and understanding of creativity than something grounded in experimental observations or neuronal mechanisms. Meanwhile, despite its consideration of neuroanatomy and existing research, Dietrich's model has not been examined experimentally in itself. Coupled with the complexity of both of these models, the lack of hard evidence makes them difficult to incorporate into any rigorous level of discussion given how little is currently known about the neuroscience of creativity. As is, the classical model simply has too many components to address properly and Dietrich's model leaves too many possible combinations to examine. To address this gap, this paper will operate on a simpler model, based largely on the modern methods of experimenting with creativity and including some of the concepts brought up by the previous models.

The model being proposed is composed of three stages: perception, manipulation, and application/synthesis. In this context, perception refers to the stimulus which instigates the creative process—the inspiration, the object being observed, the feeling being felt, the problem at hand. It is in essence the subject of the piece of art, the thought, or the eventual solution. The next step, manipulation, can be thought of as the process in which one "plays around" or "toys around" with the object of perception and its mental representation. This manipulation can take any form—destructive, constructive, combinatory. It can quite literally be "tossing around ideas" in one's own head. Finally, the application/synthesis phase involves the final production or incarnation of something new, in most cases the result of applying the aforementioned manipulation to the perception. It is important to note that at this final stage, one may deem the application inadequate and return to the start of the cycle, this time adding the previous product as a perception. The process of perception and manipulation need not be conscious although the final implementation, by definition, must be rooted in an experienced form. In accordance with the definition of creativity, originality and usefulness may combine at any one of the three stages or at any combination thereof to produce a creative result. For instance, an original and enlightening perception could be enough for a creative product given manipulation and application that are not particularly out of the ordinary. Similarly, a unique form of manipulation or even just an unusual and interesting application could be enough to turn a normal idea or art piece into a creative one.

What are the Neural Correlates of Creativity?

Experimental Approaches for Creativity

Prior to discussing the findings of neuroscience research, it is important to understand the experimental methods used for such studies. First off, most of these studies require some standard by which to measure creativity and compare creative abilities across study participants. Creativity is largely analyzed in the context of divergent thinking. Divergent thinking refers to a generative process of thought whereby many alternatives are created and analyzed. It can be thought of as a non-linear or web-like pattern of thought which is especially useful for problems with many possible solutions (e.g. organic chemistry problems, architectural/engineering problems). This is in contrast to convergent thinking, a linear, analytical, logical, and narrow approach to a task. In this vain, investigators typically quantify creativity with respect to divergent thinking using the Torrance Tests of Creative Thinking (TTCT), which include various prompts such as naming alternative uses (AU) (or common uses [CU] for a control) of an everyday object or drawing something original and giving it a creative title (Fink et al., 2006; Schlegel et al., 2015, p. 441). The results of these tests are given in a single creativity index (CI) as well as scores in several categories such as fluency, originality, abstractness, compelling depiction of complexity, and creative imagery and language (Schlegel et al., 2015, p. 442).

However, measuring creativity on its own serves little purpose. These observed measures of creativity must then be analyzed in the context of brain imaging to connect the dots between brain structure and creative ability. The most common forms of imaging utilized for this purpose include electroencephalography (EEG; e.g. Mölle et al., 1996; Jauk et al., 2012) to measure dynamic activity and brain waves, functional magnetic resonance imaging (fMRI; e.g. Marron et al., 2018) to examine functional connectivity, magnetic resonance imaging (MRI) to examine cortical volume, and fractional anisotropy (FA; e.g. Schlegel et al., 2015), which measures water diffusion directionality in white matter for the purpose of functional connectivity as well among other nuances.

Neural Predictors of Creativity

Several studies have considered the brain at rest in an effort to discover what structural features might mark one brain as inherently more creative than another. In 2014, Roger Beaty et al. published a paper on just that, examining the role of the inferior prefrontal cortex, involved with controlled memory retrieval and executive functions, and the default mode network (DMN; includes the medial prefrontal cortex [mPFC], the posterior cingulate cortex [PCC], the precuneus, and the bilateral inferior parietal lobes [IPL]), associated with attention and spontaneous cognition (Beaty et al., 2014, p. 92-93). Recent research suggests that creativity involves executive control directing memory retrieval and inhibition of salient, unoriginal ideas (Beaty et al., 2014, p. 93). Beaty et al. (2014, p. 93) cites EEG and fMRI evidence for the influence of executive processes on divergent thinking, specifically task-related activation of the inferior frontal gyrus (IFG) and inferior parietal cortex (IPC), both involved in cognitive control. Together, this information implies that connections between the DMN and inferior prefrontal cortex allow for the interaction of the conscious and unconscious mind, spurring original thought and inhibiting common associations, which marks creativity. As such, it would be reasonable to expect differences in this region of an individual's brain to correlate with differences in creativity.

Beaty et al. (2014, p. 95) distinguished a highly-creative and a low-creative group based on previous involvement in divergent thinking tests (such as the AU vs CU test mentioned earlier). At rest, an increase in functional connectivity between bilateral IFG and areas of the DMN was evident in the highly-creative group by fMRI, with the left IFG showing a stronger connectivity that was statistically significant across the entire DMN (Beaty et al., 2014, p. 95). On the right side, only the stronger connections between the IFG and bilateral IPL were significant (Beaty et al., 2014, p. 95). Outside of the DMN, the left IFG was also found to be significantly more strongly connected to several areas in the PCC and the bilateral IPC in the case of the high-creative group; the right IFG exhibited stronger connectivity to the left DLPFC as well (Beaty et al., 2014, p. 95). These findings add to previous studies which revealed creativity was correlated to increased functional connectivity between areas within the DMN itself (Beaty et al., 2014, p. 96).

One possibility which these results support is the blind variation and selective retention (BVSR) theory in which random conceptual combinations are formed without one's own volition before a controlled process evaluates the activity of this blind variation (Beaty et al., 2014, p. 96). Another idea is that failure to deactivate parts of the DMN (particularly the precuneus) during tasks which require attention allows for creativity due to the simultaneous activation of executive control and the DMN; the dominance of these two systems has been observed to fluctuate throughout the creative process with the DMN more active for coming up with ideas while executive control was more active when judging those novel ideas (Beaty et al., 2014, p. 96). Beaty et al. (2014, p. 96) simplifies this account to the claim that "the inferior prefrontal cortex and the DMN may reflect the top-down control of bottom-up processes …cognitive control mechanisms in the inferior prefrontal cortex may be responsible for directing and monitoring spontaneous activity stemming from default mode activity." This view provides a general enough framework which can then be applied to many situations. In fact, soon after presenting this idea Beaty et al. (2014, p. 96) does just that, describing how this can explain creative individuals' greater control over their own imaginations. Relating this back to the proposed model, it seems that the DMN coupled with executive control affect the manipulation and application phases as well as the decision to start the creative process all over again. However, the study design fails to take into consideration the possibility that more creative individuals may in fact experience different thought patterns at rest, in which case the differences in observed functional connectivity at rest could be artifacts of different conscious tasks being performed rather than intrinsic differences in brains organization; to his credit, Beaty et al. concedes this point (2014, p. 97).

As with any rigorous scientific finding, reproducibility is essential. Despite the ambiguity that might be associated with creativity as a field of study and the difficulties in designing neuroscience has had with producing reproducible data in this regard is impressive. Adam Sunavsky and Jordan Poppenk (2020, p. 1) were able to confirm the results of previous experiments, including Beaty et al.'s, as well as expand on them. Instead of examining divergent thinking using strictly verbal tests, Sunavsky and Poppenk (2020, p.1) incorporated visual tests, "everyday creative behavior, and creative achievement" (using an abbreviated form of the TTCT [verbal/visual ATTA], the Creative Behavior Inventory [CBI] and the Creative Achievement Questionnaire [CAQ] respectively) as well as various forms of imaging, including volumetric, white matter, and functional connectivity data. Unlike, Beaty et al., their (2020, p. 2-3) examination of the DMN included the medial temporal lobes (MTL) as part of the network, noting experimental evidence that stronger connections between the middle temporal gyrus (MTG) and mPFC have been implicated in higher levels of creativity.

Sunavsky's and Poppenk's study revealed a relationship between verbal creativity and intelligence (as measured by the full scale intelligence quotient [FSIQ]) but not visual creativity and intelligence (Sunavsky & Poppenk, 2020, p. 5). Verbal divergent thinking was also positively linked with the volume of the left and right IFG while CAQ was predicted by bilateral VMPFC volume (Sunavsky & Poppenk, 2020, p. 5). For the first time, Sunavsky and Poppenk (2020, p. 5) established a link between both the anterior cingulate cortex (ACC) and the PCC with respect to visual ATTA, CBI, and CAQ but not verbal ATTA. Looking at connectivity, FA predicted verbal divergent thought in the case of the right IFG, the left superior longitudinal fasculus (SLF), the left anterior internal capsule, left basal ganglia, and the corpus callosum; while each of these also matched at least one of the other predictors, the SLF was shown to predict every one of the four creativity measures (Sunavsky & Poppenk, 2020, p. 6). Looking specifically at functional connectivity, the connections between left hemispheric connections between the IFG and IPL correlated to verbal ATTA, the ACC-left MTG to visual ATTA and CAQ, and although not significant, the connectivity between left ACC and PCC also showed a trend towards prediciting verbal and visual ATTA (Sunavsky & Poppenk, 2020, p. 6). Whole brain analysis revealed that the cerebellum was a great indicator of creativity, with many positive and negative associations which correlated with one of the aforementioned measures (see Sunavsky & Poppenk, 2020, p. 7 for more details).

Sunavsky and Poppenk (2020, p.7) sum up the importance of these findings by explaing how their "findings underscore the relevance of executive, memory, motor, and reward systems to creative processes; support proposals that ECN [executive control network]-DMN interactions may facilitate creative processes; and confrim that neuroimaging biomarkers can be used to predict indiviudal differences in creativity." Besides confirming previous studies and the theory that the DMN helps to generate ideas which are then evaluated by the ECN, the implication of motor and reward networks is quite telling. It alludes to studies which have found differences in the dopaminergic system of creative people that lead to greater arousal and responses to sensory stimulation, flexibility, and persistence; notably, many of the regions which make up dopaminergic networks are also part of the DMN (Sunavsky & Poppenk, 2020, p. 2). The focus on the DMN and ECN confirms ideas about the manipulation and application phase, but the involvement of dopamine helps to incorporate them together even more strongly, bringing perception into the mix as well with the insight of its effects on sensory stimulation. This perception then becomes tied into manipulation and synthesis due to dopamine's invovlement in the mesolimbocortical pathway, essential to reward and pleasure, as well as the mesostriatal pathway, necessary for fluid motor function. As such, the act of envisioning something aesthetic can be coupled with the skill to transfer that to paper in a drawing for instance.

Creativity in Motion

While neural predictors at rest can help establish what makes someone intrinsically creative, how to compare people's creativity, or even how certain areas may play a role in creativity, there is no alternative to studying the brain during the creative process itself to understand just how it functions. Examining creativity in motion allows for understanding the order and timing by which brain areas connect in a way that examining functional connectivity in a resting brain cannot. Seeing how this communication between brain regions occurs in time can solidify, enhance, or even disprove theories of just how creativity can arise in the brain. It may also shed light on aspects which may make someone more capable of creativity that don't necessarily translate to different brain structure. Finally, the temporal aspect of examining the brain at work during creativity can allow for the determination of causation. Although the aforementioned studies of the brain at rest revealed neuroanatomical differences, they fail to deduce whether these changes are a result of one being more creative or the causes thereof.

Chain Free Association

Tali Marron et al. (2018, p. 40) studied creative actions using behavioral and neuroimaging approaches during chain free association (CFA) tasks. CFA requires participants to string together a "chain" of one-word associations that relate to the preceding word (Marron et a., 2018, p. 42). By examining CFA, the associative, generative aspect of creativity is targeted instead of the more executive functions which also play a role in the process (Marron et al., 2018, p. 41). After completing a series of traditional creative tests, participants were imaged using fMRI while completing CFA task that they had been trained on (Marron et al., 2018, p. 44).

At the conclusion of the study, it was apparent that CFA tasks led to increased activity of the DMN and left IFG compared to control conditions which also correlated with behavioral measures performed (Marron et al., 2018, p. 48). This implicated the DMN in the process "of verbalizing one's train of thought," specifically calling on the core of the DMN (mPFC, PCC, left temporal parietal junctions [TPJ], bilateral MTG), the prefrontal executive (left IFG) and motor areas (left medial frontal gyrus [MFG], left superior frontal gyrus [SFG]) more than typical, goal-oriented patterns of language production (Marron et al., 2018, p. 48). This group of areas seems to fit a specific sub-division of the DMN called the dorsal medial subsystem (DMPFC, TPJ, MTG, and lateral superior and inferior prefrontal gyrus) known for its role in social task that include internal reflection about one's mental state and expansion upon one's automatic thoughts (Marron et al., 2018, p. 49). The inclusion of the SFG and MFG in Marron et.al's study (2018, p. 49) highlights these area's importance for motor function while tying it to recent discoveries relating it to semantic memory, directed cognition, creative outputs like metaphors, and music improvisation (see Figure 3 for more details). This serves to further cement the dual relation of the manipulation and synthesis phases of creativity. In fact, it implies that these two phases might not seem as neutrally distinct as one would imagine.

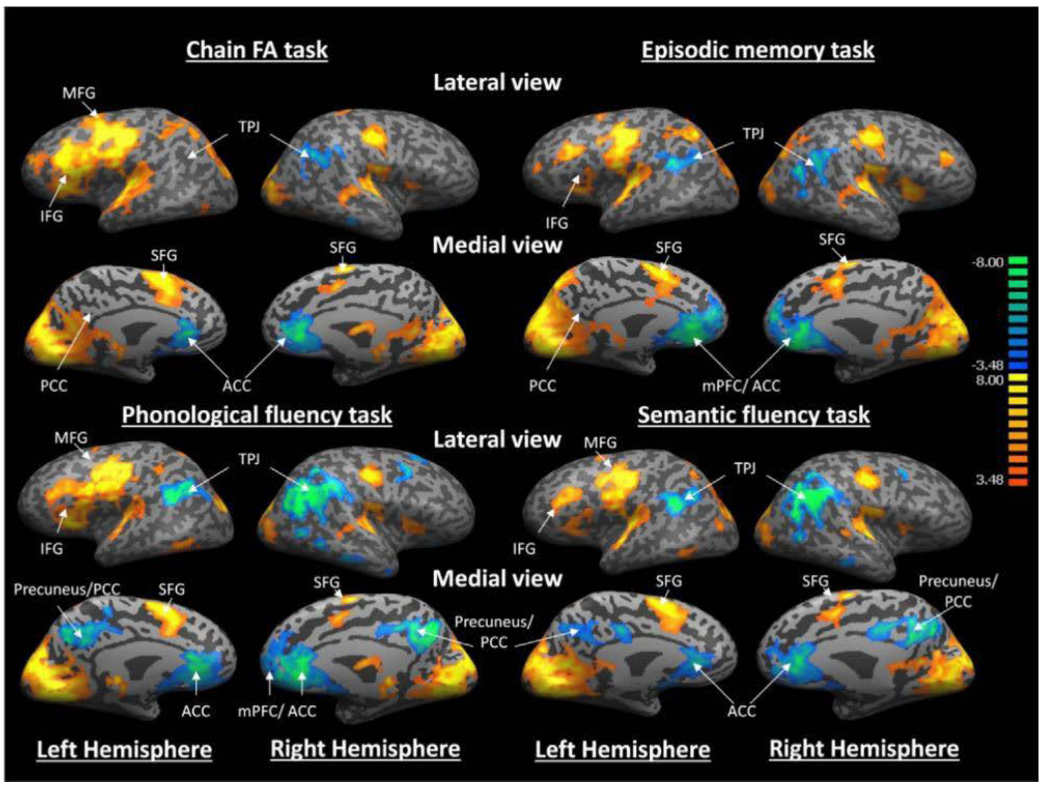

Figure 3. Whole brain activation results for fMRI during various tasks in comparison to CFA task ($p < 0.002$; Marron et al. 2018, p. 54).

Mental Representation and Manipulation

Taking the idea of creativity in motion a step more literally, Alexander Schlegel et al. (Schlegel, Kohler, et al., 2013; Schlegel, Konuthula, et al., 2013) examined the brain during the process of moving different mental representations of objects together, taking them apart, or just maintaining them in one's conscious mind. This experimental design relied on one's ability to perceive the object, manipulate it mentally, and then reach a final representation of the altered object, in accordance with the proposed model. A multitude of research, even prior to this study, suggested the involvement of the same brain areas responsible for given manipulations in the real, physical world when performing those same actions only mentally (Schlegel, Konuthula, et al., 2013, p. 1139–1140). Besides allowing for more efficient use of cortical space, this dual-functioning explains how creativity can take both tangible and intangible forms. Perhaps more substantially, this fact makes it possible, at least theoretically, to translate findings about specific implementations of creativity to a wider array of creative forms.

An initial study by Schlegel et al. (2013, p. 16279) revealed that the DLPFC, PFC, posterior precuneus, and occipital cortex are the main brain regions which form a network that enables manipulating objects of visual imagery (see Figure 4 for more details). More specifically, the DLPFC seems to be required for maintaining anything within working memory and attending to it regardless of the task at hand, with evidence for concurrent activation of the posterior parietal cortex (PPC; Schlegel, Kohler, et al., 2013, p. 16279). By being involved in both maintaining and manipulating any mental representation, these two areas likely form the essence of the system that allows for conscious cognitive operations that require flexibility as well as analysis (Schlegel, Kohler, et al., 2013, p. 16279). The occipital cortex has been shown to be specifically involved in processing internal visual experiences as well as externally generated perception; it can even be used to predict what a participant is visualizing during a dream (Schlegel, Kohler, et al., 2013, p. 16280). Being that the OCC is a large part of the visual cortex, this finding confirms the aforementioned idea that the same brain regions are implicated in mental and physical correlates of the same function. There is a clear network of involved brain regions as the precuneus, particularly the posterior precuneus, becomes more connected to the

DLPFCC, PPC, and OCC during mental visual manipulations acting like a hub for the mental workspace to permit conscious information processing (Schlegel, Kohler, et al., 2013, p. 16280). Perhaps the most important finding of the study was a separate network for mental maintenance than mental manipulation, both involving many of the same brain regions with the MTL as the hub in the latter.

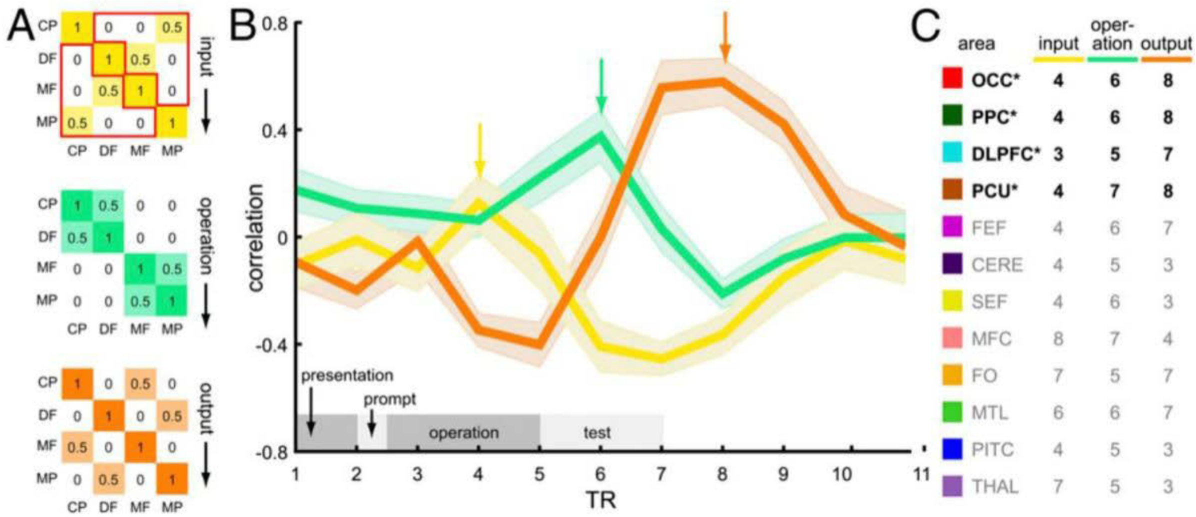

Figure 4. Temporal activation during mental operations. (*A*) Model similarity based on the four tasks involved in the experiment and the input, operation, and output. (*B*) OCC correlations during different time-points across models. (*C*) Peak correlation times for the regions of interest (ROIs) involved in the study. CP, construct parts; DF, deconstruct figure; MP. maintain parts; MF, maintain figure (Schlegel, Kohler, et al., 2013, p. 16280).

To develop this discovery further, Schlegel et al. (Schlegel, Konuthula, et al., 2013) soon delved into the details of this manipulation network and its interaction with the mental workspace. This time, three-dimensional objects were kept in working memory with the mental manipulation occurring in the form of rotation (Schlegel, Konuthula, et al., 2013). Once again, the involvement of the same motor network sued for physical mental rotation was involved, becoming "dynamically integrated with a distributed, cortex-wide neural network underlying the mental workspace … support[ing] a model of the mental workspaces as consisting of a flexible core network that can dynamically recruit domain-specific subnetworks for specific functions, much like a general contractor would employ specialists as needed for specific jobs" (see Figure 5; Schlegel, Konuthula, et al., 2013, p. 1149). This might be able to explain a very simple phenomenon which one might observe in a myriad of situations: if asked to rotate something mentally, one will often act as if he or she is rotating it in one's own hand, moving the hand as they imagine the corresponding results. It seems that improvements in creativity, especially over a short period of time, are tied to changes in motor abilities at corroborating mental representations rather than changes in perception (Schlegel et al., 2015). However, this requires further exploration across multiple forms of art and differing lengths of time.

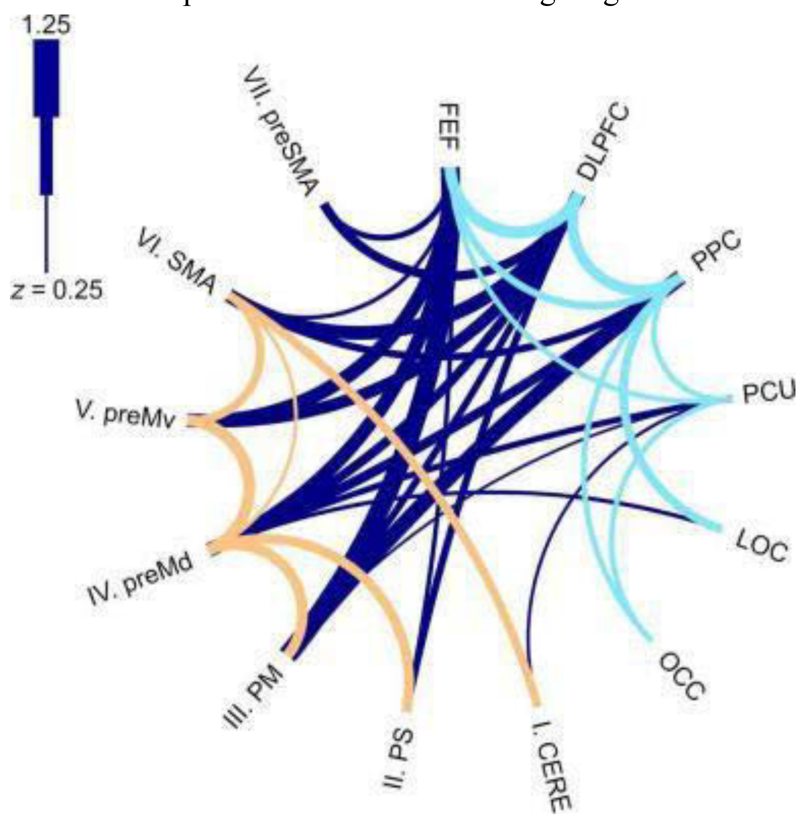

Figure 5. ROI cross-classification results showing connections within the motor network in light orange, the core mental workspace network in light blue, and across the two networks in dark blue (Schlegel, Konuthula, et al., 2013, p. 1148).

Creativity and The Abnormal Brain

After examining creativity in the brain under normal conditions, at rest and in motion, it might be helpful to explore the creative experience in the diseased or abnormal brain. Such an approach has been profoundly insightful throughout the history of neuroscience as a field, permitting experiments that would never be permitted due to ethical or practical concerns (e.g. the case of Phineas Gage, who lost a portion of his frontal lobe in a freak accident). Examining brains in which a specific feature is lacking allows approaching similar problems from a different angle.

Schizophrenia and Autism

Trying to understand neuroscience through the lens of disease might prove especially profound in the case of creativity due to the common claim that psychotic conditions, such as schizophrenia, bipolar disorder, and major depressive disorder, are often accompanied with increased creativity (Crespi & Badcock, 2008, p. 241). Some cited examples of this include Ludwig van Beethoven, Edvard Munch, Vincent van Gogh, Georgia O'Keefe, Ernest Hemingway, and Edgar Allen Poe (Berman, 2015; Keenan, 2020).

The most well-studied of these diseases with respect to its relation to creativity is schizophrenia. Schizophrenia has been associated with deficits of the left-hemispheric language function which might suggest greater reliance on the right-hemisphere for thought and language processing and thus a broader semantic understanding with the development of more loose associations that often come off as delusions (Crespi & Badcock, 2008, p. 250). Taking this into account with the general findings of creativity research, it can be postulated that schizophrenia affects creativity in two ways. First, schizophrenia increases the frequency of original ideas. Secondly, it might be reasonable to suggest that schizophrenia also decreases one's ability to properly evaluate these novel ideas to assign them worth or relevance. Perhaps creativity is then associated with creativity simply due to the increased generation of unique entities allowing for the production of better ideas as a function of chance or maybe the previously mentioned “creative geniuses” suffered cases in which their evaluative networks were not heavily affected. Michael Fitzgerald and Ziarih Hawi provide a more pertinent idea whereby they explain that “Although creativity in schizophrenia diminishes after the onset of the condition, family members with less severe traits of the condition can show great creativity, reflecting perhaps broader phenotype features” (Fitzgerald & Hawi, 2008, p. 269). What is perhaps even more telling is the fact that dopamine agonists have been used in schizophrenic patients to restore left-hemisphere language dominance (Crespi & Badcock, 2008, p. 250). Not only does this build up on dopamine’s role in creativity through its effects on reward, pleasure, and motor function, but it also adds the possibility that dopamine might be implicated in the idea evaluation aspect of creativity. Furthermore, it suggests that language, specifically in the left hemisphere, is largely responsible for this idea selection while the right hemisphere is involved in the “explosion” of ideas that accompanies creative pursuits. A study by Andreas Fink et al. ((Fink et al., 2014, p. 378) corroborated this idea, confirming that the originality (measured via AU vs CU divergent thinking test) involved with creativity accompanied reduced deactivation of right parietal brain regions and the precuneus in high-schizotypy patients compared to low-schizotypy patients (see Figures 6 and 7; Fink et al., 2014, p. 379). The PCC and precuneus are believed to be tonically active, continuously gathering internal and external information to create a representation of one’s own world (Fink et al., 2014, 384). It (as well as the right parietal brain regions for the most part) typically deactivates during goal-directed actions to focus attention; the fact that this pattern is decreased in creativity allows for a broader form of attention (Fink et al., 2014, 384). Although this finding might explain creativity in schizophrenic patients, it may also imply that creative people are more likely to develop some form of psychosis (Fink et al., 2014, p. 379).

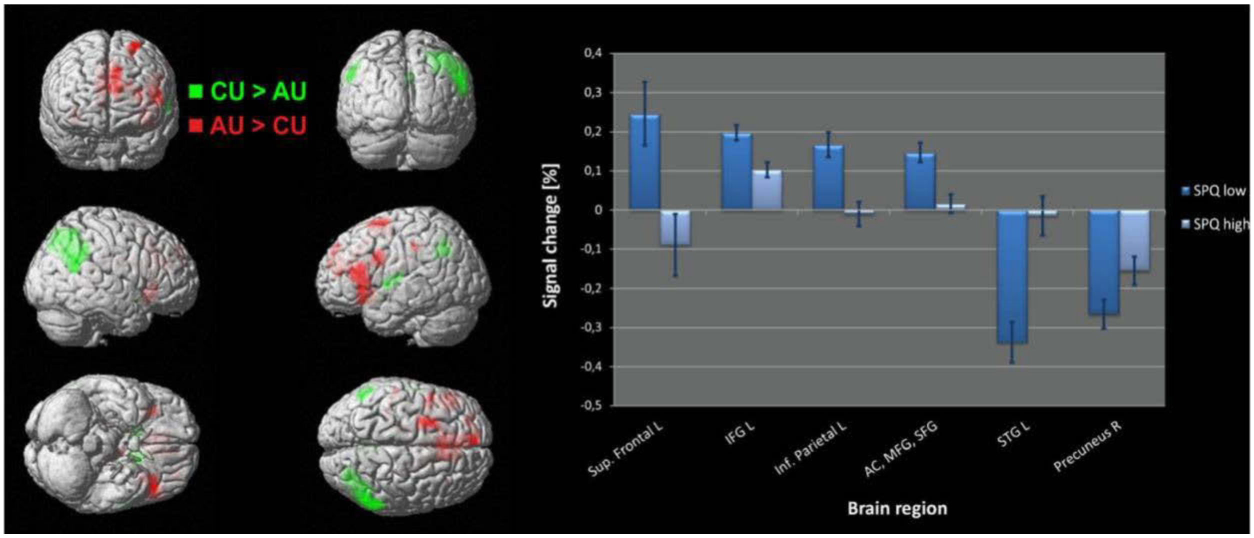

Figure 6. Significant activation clusters (left) where CU > AU (green) or AU > CU (red). Plots (right) indicate differences in activation of brain regions in low-schizotypy (SPQ low; dark blue) and high-schizotypy (SPQ high; light-blue) during creative task (Fink et al., 2014, 387).

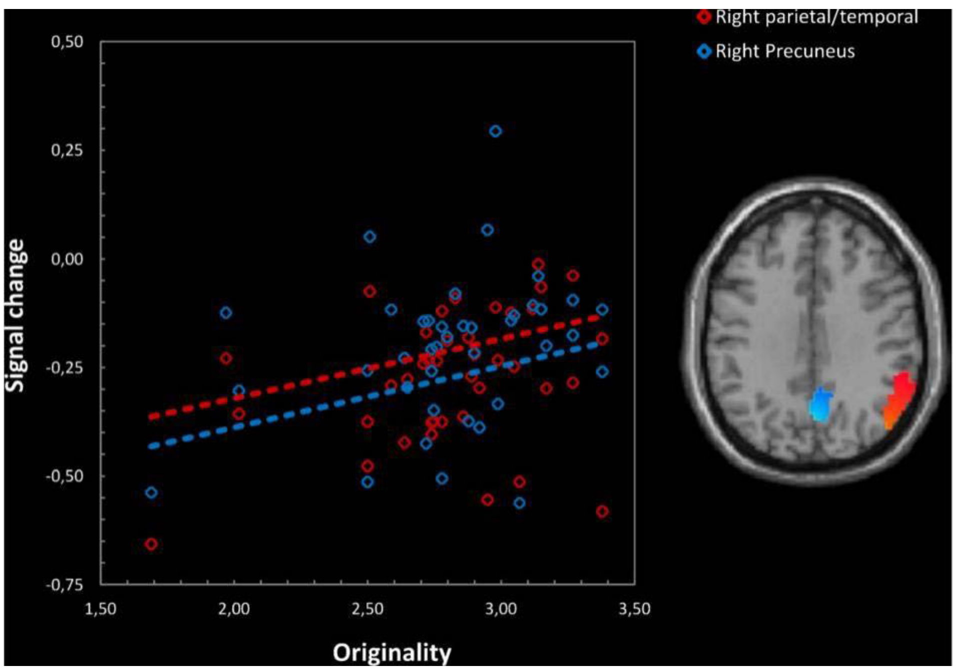

Figure 7. Brain regions (right precuneus, blue; right parietal/temporal regions, red) with significant correlations between activity and originality (according to fMRI; Fink et al., 2014, 388)).

The relationship between disease and creativity can also be viewed from the opposite lens. Bringing autism into the picture, often considered the other side of the spectrum of neurodevelopmental/mental illness disorders (compared to schizophrenia), allows for yet another helpful perspective. Unfortunately, there has been little research exploring the relationship between autism and creativity. Still, there are several points which stick out when considering our general understanding of autism and similar disorders. The symptoms of autism include less pretend play, suggesting more limited imagination, less symbolic representation, and an increase in repetitive or compulsive behaviors, whether specific motor patterns or ideological patterns (Crespi & Badcock, 2008, p. 250). According to the accepted definition of creativity, this would align with a less creative phenotype, with less original idea production and perhaps even a diminished capability to evaluate the appropriateness of certain ideas. This limited ability to evaluate is evident in the tendency of patients suffering from autism to perform inappropriate behaviors, often social, at inappropriate times. The neuroanatomy of autism also supports many of the findings relating to creativity. In fact, with respect to the decreased left-language language function in schizophrenia, autism exhibits similar right-hemisphere language dominance due to brain asymmetry wherein the right-hemisphere's cortical structures are enlarged (Crespi & Badcock, 2008, p. 250). While this might seem to contradict the suggestion that the diminished role of left-hemisphere language centers in inhibiting free-thought in favor of focused attention, one must take into account the reversed lateralization of language in many cases of autism (Crespi & Badcock, 2008, p. 250). As such the increased size and dominance of right-hemisphere language processing centers corresponds to an increased influence of left-hemisphere language centers in a typical brain, thus explaining the repetitive behaviors and lack of original ideas associated with autism. Changes

Brain Lesions

Studying specific lesions allows even more specific understanding of creativity, localized to one brain area and its role, than disease-inspired models. In this light, Simone Shamay-Tsoory et al. (2011, p. 178-179) examined how lesions in different brain areas affected original response, defined as "the interaction between generating unique new ideas and inhibiting stereotypical automatic thinking." Patients with lesions of the mPFC exhibited impairments in creativity and originality with right-hemisphere lesions of the mPFC being the most impactful; still, right-hemisphere lesions in general had a larger effect on creativity than left-hemisphere lesions (according to AU tasks and TTCT; Shamay-Tsoory et al., 2011, p. 183). While the mPFC has been tied to creative cognition, the ACC has been thought to increase activity when their his high probability of making an error in order to mediate response selection and processing of conflicts (Shamay-Tsoory et al., 2011, p. 183). Changes in originality and creativity present in patients with mPFC lesions may be partly (but certainly not completely) as a result of the ACC lesion more specifically (Shamay-Tsoory et al., 2011, p. 183). The other areas of the mPFC and their roles are yet to be understood. Creativity has been related generally to prefrontal activity, including stronger alpha activity synchronization and phase coupling (Shamay-Tsoory et al., 2011, p. 179). Notably, the ACC has been implicated in autism and autism-like disorders (such as Prader-Willi Syndrome), expanding on the connection between diminished creativity and autism due the region's role (Varghese et al., 2017, p. 543). The role of the prefrontal cortex is not incredibly however when considering other studies which suggest deactivation thereof allows for creativity by inhibiting more control over thoughts, such as in the case of musical improvisation (Schlegel et al., 2015, p. 441). On the other hand, originality of patients with left posterior parietal and temporal cortices and left IFG lesions increased slightly while left-hemisphere legions in general did not exhibit this pattern (Shamay-Tsoory et al., 2011, p. 183). The greater the impairment of the left parietal and temporal cortices, the greater the originality scores were (Shamay-Tsoory et al., 2011, p. 183). In accordance with aforementioned discussions about the influence of language in limiting creativity, the left IFG and left parietal and temporal cortices are both involved in verbal information processing and language production respectively; there are several reports of newly developed artistic behavior following brain damage to these areas as well as in the case of progressive aphasia or semantic dementia (Shamay-Tsoory et al., 2011, p. 183-184). The exploration of creativity in the realm of language, such as forms of creative writing and literature, might provide valuable information with regards to such discussions.

What are the Implications for the Neural Correlates of Consciousness?

Despite how far the field of neuroscience has come in addressing the neural correlates of creativity, a notoriously elusive concept, there is still much to be done. Not only do the studies mentioned bring up questions about the roots of creativity, but they elucidate even more areas for the wider exploration of consciousness. In this respect, the current collection of knowledge surrounding creativity already sheds light on the neural correlates of consciousness (NCC) while providing for more specific areas of focus to look into.

Location of the NCC

In order to better understand consciousness, it is perhaps most important first to find out where consciousness arises in order to probe it more. Cristof Koch (2004, p. 99) seems to believe that pyramidal cells are responsible for consciousness, with NMDA receptors and excitatory glutamatergic neurons of particular significance. However, the aforementioned implication of dopaminergic neurons in creativity seems to contradict this idea. In fact, there seems to be very little neuronal evidence to help narrow down the NCC to a specific morphology or base unit of a neuron’s size. Many studies on creativity have discovered significant findings with relation to white matter rather than gray matter through FA imaging. As a result, the importance of glial cells and myelin cannot be discounted just yet. Much of the difficulty with singling down a specific biological subunit for creativity lies in the nature of brain imagery. Brain activity is almost exclusively monitored, especially in humans, through its effects rather than directly (e.g. most forms of brain imaging rely on measuring neural activity through its effects on water or blood). Yet, there is hope. The DMN seems to be the one constant in almost all the aforementioned studies and many more which explore effects on conscious experience. While Koch (2014 , p. 88) postulates an NCC_e, an enabling NCC responsible for general consciousness, as well as separate NCCs responsible for specific qualia, a similar but more general approach might be best until more research is done.

Relationship Between Different NCCs

The next question that arises is how those different experiences are related. While NCCs and their relations to each other might be a reasonable suggestion to describe simple qualia such as those involved in vision (the experience of specific colors, brightness, etc.), it becomes much more difficult once large brain networks are involved. Columnar organization as Koch (2004) allows NCCs to fit beside each other like puzzles or to overlap. However, there is little other possibility. There seems little to no exploration of neural organization in the form of superimposition (this might be largely due to the difficulties in exploring such a possibility using current imaging techniques). Once neural networks enter the conversation, thinking about the relationship between different NCCs in a similar manner becomes nearly impossible. Each area of the brain has been shown time and times again to be involved in a multitude of different functions. The brain is an incredible piece of machinery which relies on areas having multiple functions in order to make the most of efficient use of valuable cortical space. As such, if countless NCCs overlap over the same region, the concept of the NCC becomes anything but helpful. There becomes no conceivable way to elucidate a specific experience by stimulating one area. Rather, it becomes inevitable (and this might very well be the case in reality) that the whole pathway responsible for an experience, from the stimulus response to the very top-most correlate, become active to give rise to a specific experience. For this reason, the idea of the NCC must not be adopted, especially at this stage. The current state of the art still requires a grounding in neural networks in general before reaching any form of such broad generalizations.

Higher-Level Correlates of Consciousness

Finally, the application of creativity studies on the broader concept of consciousness begs one to reimagine just what an experience or perception is. As a higher-level form of cognition unlike the simple qualia mentioned previously, there is no real consensus on what it means to experience creativity. If one were to activate the so-called NCC of creativity, what would he or she expect? Would the result be a person staring to create a creative work, perhaps an art piece? Would one simply feel creatively inspired? Would one feel as if he or she was observing an especially compelling piece of art? These questions highlight just why the field should not get ahead of itself. Models are meant to simplify science in order to break it down further and gain a more accurate understanding thereof. The idea of the NCC poses many more questions than it answers. Considering consciousness as a lone process inherently forces scientists to move away from the idea of the conscious and unconscious fluidly interacting. It begs the question for why the field is not search for a neural correlate for the unconscious. In essence, this may be a blinding to objective science, inspired by our own experience. While there is certainly value to exploring the subjective, the NCC does not seem the best way to do so. It fails to leave room for the field to grow. For instance how would a small unit like the NCC explain the idea of nature versus nurture. Would one's creative abilities develop as a function of one singular neural column's change? In short, the consideration of higher-level experiences seems to be the fatal blind-sight of the concept of an NCC. The points on which such an idea is founded simply are not compatible with the complexity of the human experience (see Figure 8).

1. **Explicit Representation.** The attribute should be explicitly represented on the basis of a columnar organization.
2. **Essential Node.** The attribute can't be perceived when the brain region containing the NCC is destroyed or inactivated.
3. **Artificial Stimulation.** Appropriate electrical or magnetic stimulation should lead to perception of the attribute.
4. **Correlation between Perception and Neuronal Activity.** The onset, duration, and strength of the relevant neural "activity" should correlate on a trial-by-trial basis with awareness of the attribute.
5. **Stability of Perception.** The NCC should be invariant to blinks and eye movements that disrupt sensory input but not perception.
6. **Direct Access to Planning Stages.** The NCC neurons should project to the planning and executive stages.

Figure 8. "Necessary Conditions for the NCC of Any One Stimulus Attribute" (Christof Koch, 2004, p. 114)

Conclusion

Due to the universal involvement of the DMN as well as the evidence of different networks recruited during specific activities and experiences, it seems more accurate to suggest that the DMN is responsible for consciousness and is able to recruit other brain areas in order to modulate its own activity and one's overall experience. This permits for specific areas to function multiple roles distinctly while also allowing for significant efficiency. However, there is still much to be explored. The current state of the field is something to be excited about, especially due to the reproducibility which has been present across many studies. In the search for consciousness and creativity however, scientists must seek not to limit themselves. They must allow themselves freedom to explore the possibilities without reaching for premature boxes to confine themselves to. The key to creativity as most people know without having done any research is thinking outside of the box.

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