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Review article

Creative cognition and dopaminergic modulation of fronto-striatal networks: Integrative review and research agenda

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ABSTRACT

Creative cognition is key to human functioning yet the underlying neurobiological mechanisms are sparsely addressed and poorly understood. Here we address the possibility that creative cognition is a function of dopaminergic modulation in fronto-striatal brain circuitries. It is proposed that (i) creative cognition benefits from both flexible and persistent processing, (ii) striatal dopamine and the integrity of the nigrostriatal dopaminergic pathway is associated with flexible processing, while (iii) prefrontal dopamine and the integrity of the mesocortical dopaminergic pathway is associated with persistent processing. We examine this possibility in light of studies linking creative ideation, divergent thinking, and creative problem-solving to polymorphisms in dopamine receptor genes, indirect markers and manipulations of the dopaminergic system, and clinical populations with dysregulated dopaminergic activity. Combined, studies suggest a functional differentiation between striatal and prefrontal dopamine: moderate (but not low or high) levels of striatal dopamine benefit creative cognition by facilitating flexible processes, and moderate (but not low or high) levels of prefrontal dopamine enable persistence-driven creativity.

1. Introduction

Compared to other species, humans have unsurpassed ability to explore, to seek and create novelty, and to enjoy it. Such ability to create and innovate allows humans to flexibly adapt to, and prosper in, rapidly changing environments, to increase social standing and reputation, to perform complex tasks, and to make high quality decisions (Hennessey and Amabile, 2010; Miller, 2000; Nijstad et al., 2010; Runco, 2004; Sternberg, 1999). Although creativity is often seen as rather elusive (Plucker and Renzulli, 1999; Runco, 2004), psychological science converges on an operational definition of creativity as the production of outcomes (e.g., ideas, products, services) that are original, yet potentially useful (Runco and Jaeger, 2012). Creative performance is influenced by a range of cognitive process(es) such as accessing remote associations and divergent thinking, exogenous factors such as extrinsic rewards and time pressure, and characteristics of the creative person such as approach orientation (in which motivation and behavior are regulated by, and directed towards, desired and appetitive stimuli), openness to experience, intelligence, and vulnerability to psychopathology (Amabile, 1996; Baas et al., 2008, 2016; Runco, 2004; Sternberg, 1999).

In the creativity literature, a distinction is made between 'little c' and 'big C' creativity (Gardner, 1993). Whereas 'big C' creativity refers to eminent creative achievements of brilliant scientists such as Marie Curie and Albert Einstein, of great inventors such as Thomas Edison, or of famous artists such as Emily Dickinson, Pablo Picasso, or The Beatles, 'little c' creativity refers to relatively mundane contributions and everyday creativity, expressed in people's novel use of language, their ability to create and apply new mental categories to organize experiences, and their ability to mentally manipulate objects (Kaufman and Beghetto, 2009; Ward et al., 1999). Here we focus on 'little c' creativity, for two reasons. First, it is important in day-to-day life: it helps us adapt to changing circumstances, to solve everyday problems, and to create new opportunities (Richards, 2007). Second, the cognitive processes that support 'little c' creativity may also operate in cases of 'big C' creativity (Guilford, 1950; Ward et al., 1999), and the study of 'little c'

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creativity may therefore contribute to a better understanding of creative genius (Nijstad et al., 2010).[2]

Underlying the cognitive processes accounting for 'little c' creativity are neural circuitries that may be temporarily or more chronically (de-) activated. Uncovering such neural circuitries may thus offer a unifying framework for understanding how person and situation characteristics influence creativity. Recent advances in neurobiology and (cognitive) neuroscience converge on several candidate regions and networks in the human brain that seem to be involved in creative cognition, including prefrontal, parietal, and temporal circuitries, and the striatum (e.g., Abraham et al., 2012; Beaty et al., 2016; Mayseless et al., 2011). For instance, creativity is associated with the activation of prefrontal circuitries that are involved in the controlled manipulation of information and executive functioning (Abraham et al., 2012; Barr et al., 2014; Benedek et al., 2014; De Dreu et al., 2012; Dietrich and Kanso, 2010; Gonen-Yaacovi et al., 2013; Metuki et al., 2012). Creativity also seems to be related to the striatum, which is part of a sub-cortical network involved in reward processing, habitual behavior, and flexible updating of goal representations and switching between task strategies (Abraham et al., 2012; Cools and D'Esposito, 2011; Ikemoto, 2007; Mayseless et al., 2013; Zabelina et al., 2016). Interestingly, the striatum and prefrontal cortex are strongly interconnected and conditioned by the neurotransmitter dopamine (Alexander et al., 1986). Moreover, growing evidence from neurobiology shows that dopaminergic modulation of such fronto-striatal circuitries regulates the balance between flexibility and persistence (Cools et al., 2007), two key cognitive processes that support creativity (Nijstad et al., 2010).

The purpose of this review is two-fold. First, we review evidence for a functional differentiation between striatal and prefrontal dopamine: moderate (but not low or high) levels of striatal dopamine benefit creative performance by facilitating flexible processes, and moderate (but not low or high) levels of prefrontal dopamine enable persistence-driven creative outputs. Second, we aim to integrate and connect this possibility with research using standardized tests to measure creative cognition and performance conducted in social, personality, and clinical psychology. In combination, these two aims integrate recent insights into the neural underpinnings of creative cognition and performance, and provide a research agenda for further understanding the neurocognitive underpinnings of creativity.

We proceed as follows. Section II reviews contemporary scientific approaches to (measure) human creative cognition, suggesting that creative outputs derive from two distinct yet interrelated cognitive processes—flexibility (allowing people to consider different task approaches and unconventional perspectives) and persistence (enabling people to work on creative problems attentively and thoroughly over longer periods of time). Section III summarizes neurobiological work on dopaminergic modulation of fronto-striatal circuitries in relation to flexibility and persistent processing and a model of dopaminergic modulation of creativity via fronto-striatal brain circuitries is proposed. Section IV reviews the evidence for our model and integrates currently scattered and oftentimes indirect research evidence on the relationship between striatal and prefrontal dopamine activity, and flexibility and persistence in creativity. Section V examines knowledge gaps, avenues for future research, and possibilities for creative enhancement. Section V also addresses possible other neural networks and circuitries that assist creativity in addition to the fronto-striatal circuitries addressed here.

[2] The relationship between little c and big C creativity is not necessarily straightforward. For example, the relationship between creative performance on laboratory tasks and creative achievements outside of the laboratory (e.g., in the classroom, or in one's profession) can be rather weak (Baer, 2011a; Kim, 2008). A discussion of possible explanations in terms of measurement issues, the role of domain-specific expertise, and state/trait-based moderators is beyond the scope of this article (but see, e.g., Baer, 2011b; 2016; Kaufman, 2016; Runco and Acar, 2012; Simonton, 2007).

2. Demystifying creativity

To study creative cognition and its underlying processes, scientists have developed and used a range of tasks and measures, some of the more frequently used ones are shown in Table 1. Many of these tasks directly measure creative outputs – ideas or insights that are novel yet fitting and potentially useful – but also provide good insight into the underlying cognitive processes. Consider the widely used Alternative Uses Task, in which individuals write down as many unusual ways to use a common object, such as a brick or a tin can (Guilford, 1967). Ideas are scored in terms of *originality* (the extent to which the ideas are unusual and novel), and in terms of underlying cognitive processes as reflected in for example *fluency* (the number of generated ideas) and *flexibility* (the number of different conceptual categories that the ideas belong to). There is good evidence that both fluency and flexible processing benefit originality (Nijstad et al., 2010).

In addition to such open-ended idea generation tasks, creativity has been examined using insight tasks. Insight tasks typically require unexpected and unusual approaches or mental restructuring of information about a presented problem (both flexible and divergent processing), as well as the ability to engage in constrained and confirmatory search processes to identify the correct solution (Bowden et al., 2005; Cropley, 2006). Consider the frequently used Remote Associates Test, in which participants receive series of three words that are only remotely related to each other (e.g., *falling*, *actor*, *dust*) and are instructed to generate a word that relates to all of these three words (i.e., *star*) (Mednick, 1962). To find the correct solution, people rely on divergent thinking to sample potentially correspondent attributes and relations associated with the three provided words, but test a possible solution through convergent processing (Chermahini and Hommel, 2010; De Dreu et al., 2014; Folley and Park, 2005).

2.1. Two pathways to creativity

The processes listed in Table 1 may suggest that it is divergent, remote, and flexible thinking that promotes original ideation and creative problem solving. However, such intuition is best characterized as a half-truth according to the Dual Pathway to Creativity Model (De Dreu et al., 2008; Nijstad et al., 2010). The model expands on earlier work into creative cognition and problem-solving (e.g., Amabile, 1996; Ashby et al., 1999; Mednick, 1962; Simonton, 2003; Ward et al., 1999) and conjectures that creative outputs result from two distinct cognitive processes—flexibility versus persistence. The *flexibility pathway* includes a broad attentional scope (a tendency to perceive holistic and global rather than detailed structures), facilitated access to semantic concepts with lower *a priori* accessibility, divergent thinking, and flexible switching between perspectives (Mayseless et al., 2013; Runco et al., 2011; Silvia et al., 2008). As such, the flexibility pathway incorporates a range of (lower-level) cognitive processes and skills such as switching between cognitive sets or response rules (Alexander et al., 2007) and the inhibition of a dominant response in favor of a more appropriate response (Dreisbach and Goschke, 2004; also see Ashby et al., 1999; Nijstad et al., 2010).[3] Alone and in combination, these

[3] Within the cognitive neurosciences and psychology, the term flexibility is used to refer to a variety of cognitive processes or skills (Eslinger and Grattan, 1993; Ionescu, 2012; Zabelina et al., 2015), including switching between cognitive sets or response rules (Kehagia et al., 2010), inhibition of a dominant response in favor of a more appropriate response (Dreisbach and Goschke, 2004), manipulation of information in working memory (Durstewitz and Seamans, 2008), and goal-directed exploration (Cools, 2012). In addition, different types of flexibility associate with activity in different parts of the brain (e.g., Eslinger and Grattan, 1993; Ravizza and Carter, 2008). We refrain here from solving this definitional issue. However, to avoid confusion, we refer to flexibility as the ease with which people break the set of typical associations and consider different perspectives or alternatives during idea generation or problem solving (Ashby et al., 1999; Nijstad et al., 2010); *cognitive* flexibility is used to refer to the ease with which people can switch among different tasks, sets, strategies, or goal representations