A Neuroeconomic Framework for Creative Cognition

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Abstract

Neuroeconomics is the study of subjective preferences and value-based decision making. We present a novel framework that synthesizes findings from the literatures on neuroeconomics and creativity to provide a neurobiological description of creative cognition. It proposes that value-based decision-making processes and activity in the locus coeruleus-norepinephrine (LC-NE) neuromodulatory system underlie creative cognition, as well as the large-scale brain network dynamics shown to be associated with creativity. This framework allows us to re-conceptualize creative cognition as driven by value-based decision making, in the process providing several falsifiable hypotheses that can further our understanding of creativity, decision making, and brain network dynamics.

Keywords: creativity, neuroeconomics, value-based decision making, locus coeruleus-norepinephrine (LC-NE) system, network dynamics

A Neuroeconomic Framework for Creative Cognition

According to the standard definition, products that are both novel and useful within a given context are considered to be creative (Diedrich, Benedek, Jauk, & Neubauer, 2015; Runco & Jaeger, 2012; see also Sternberg, 1999). However, despite notable recent advances in the neuroscience of creativity (for reviews see Jung & Vartanian, in press; Vartanian, Bristol, & Kaufman, 2013) and a wealth of correlational data from brain imaging studies (for meta-analyses see Boccia et al., 2015; Gonen-Yaacovi et al., 2013), a critical question that remains unanswered is how the brain produces ideas that satisfy the above two criteria. Part of this shortcoming may be due to the lack of mechanistic accounts of brain processes that underlie creative cognition.

We work from the assumption that a complete account of creativity will require not only an understanding of its cognitive architecture, but also the neural systems that underlie it. Towards that end, we propose a novel and neurologically plausible framework for creative cognition. This framework has three components: First, it proposes a neuroeconomic approach to creativity, suggesting that value-based decision-making processes underlie creative cognition. Second, it describes how the locus coeruleus-norepinephrine (LC-NE) neuromodulatory system could support creative cognition by adaptively optimizing utility or subjective value. Third, it suggests that the dynamic interactions within and between brain networks observed during creative cognition are driven by activity in the LC-NE system and the interconnected brain regions that compute and evaluate subjective value. By bringing together a diverse range of findings from different fields, this framework provides a new conceptualization of creative cognition as driven by value-based decision making. It also points the way to future research by providing novel and testable hypotheses that are relevant to the fields of creativity, decision making, and brain network dynamics.

Value-based decision-making processes underlie creative cognition

Neuroeconomics of creative cognition

Neuroeconomics is a young but thriving interdisciplinary field that examines the neurobiological and computational underpinnings of value-based or economic choices (Camerer, 2013; Rangel, Camerer, & Montague, 2008; Konovalov & Krajbich, 2016). Value-based choices are pervasive in everyday life, ranging from the mundane to the consequential. Essentially, any choice that requires us to express our subjective preferences and to choose from among two or more alternatives is a value-based choice (e.g., Do you want an apple or an orange? Do you prefer the universe or the multiverse model?). These choices often lack an intrinsically correct answer, and depend instead on subjective preferences. They are called *valued-based* or *economic* choices because most neurobiological models of decision making have integrated economic constructs such as utility or value maximization into their frameworks. These models assume that decision makers make choices by assigning a value to the available options, and then select the option with the highest value (Kable & Glimcher, 2009; Padoa-Schioppa, 2011; Rangel et al., 2008).

The basic premise of the present framework is that creative cognition is similarly supported by value-based decision-making processes. In its stronger form, creative cognition would be considered a form of value-based decision making. That is, process-wise, creative cognition resembles making choices in everyday settings because it too involves generating multiple ideas and then selecting the idea with the highest subjective value amongst generated ideas (see Vartanian, 2011). Consistent with this proposal, the philosopher Paul Souriau (as cited in Campbell, 1960, p. 386) noted that “of all of the ideas which present themselves to our mind, we note only those which have some *value* and can be utilized in reasoning” (italics added).

Moreover, within the psychological literature, the idea that creativity involves thought processes that resemble value-based decision making is not without precedent. One well-known example is the family of Blind Variation Selective Retention (BVSR) models, in which creativity includes generation and selection steps, the latter of which incorporates evaluative processes (Basadur, Graen, & Green, 1982; Campbell, 1960; Simonton, 1999; see also Vartanian, 2011). Specifically, after an initial step that involves the generation of candidate ideas, the second step involves the engagement of evaluative process for selecting the best idea(s) (based on certain criteria). Another example is Sternberg and Lubart's investment theory of creativity (Lubart & Sternberg, 1995; Sternberg, 2006, 2012), according to which creative people excel at pursuing and further developing ideas that have growth potential, but happen to be unknown or out of favor within the field. In this sense, they "buy low and sell high in the realm of ideas" (Sternberg, 2012, p. 5). Creative idea generation therefore involves evaluative processes for selecting unpopular ideas for further nurturing, and is partly influenced by environmental factors that determine the selection criteria. However, although both BVSR and the investment theory of creativity acknowledge a relationship between utility maximization and creative cognition, they do not provide a neurological and mechanistic framework of how utility maximization contributes to creativity. In what follows we will review evidence suggesting a relationship between value-based decision making and creativity, and will argue that the former helps to realize the latter.

One of the most robust findings from neuroeconomic research is that across species and studies, a specific set of brain regions, including the ventromedial prefrontal cortex (vmPFC), the orbitofrontal cortex (OFC), posterior cingulate cortex (PCC), and the striatum, are involved in value-based decision making (Padoa-Schioppa & Cai, 2011; Rangel et al., 2008; Rich & Wallis, 2016) (Figure 1). For example, functional magnetic resonance imaging (fMRI) studies have

shown that blood-oxygen-level dependent (BOLD) signals in the vmPFC correlate with behavioral preferences for beverages (McClure et al., 2004) and the subjective value of delayed monetary rewards (Kable & Glimcher, 2007; McClure, Laibson, Loewenstein, & Cohen, 2004). Crucially, converging evidence from fMRI (Bartra, McGuire, & Kable, 2013; Clithero & Rangel, 2014; Grueschow, Polania, Hare, & Ruff, 2015), lesion (Buckley et al., 2009; Camille, Griffiths, Vo, Fellows, & Kable, 2011; Hogeveen, Hauner, Chau, Krueger, & Grafman, 2016), and electrophysiological (Padoa-Schioppa, 2011; Padoa-Schioppa & Assad, 2006; Rich & Wallis, 2016) studies suggests that a set of brain regions comprised of the OFC, vmPFC, medial prefrontal cortex (mPFC), and PCC not only represent value, but also evaluate choice alternatives during value-based decision making.

This body of evidence has led to the “common currency” hypothesis, according to which a small set of specific brain areas appears to encode the subjective values associated with many different types of rewards on a common neural scale, regardless of the variation in the stimulus types giving rise to the evaluations (Levy & Glimcher, 2012). Perhaps not surprisingly, the same set of regions also underlies aesthetic experiences, given that our preferences for attractive faces (Kim et al., 2007; O'Doherty et al., 2003), harmonious color combinations (Ikeda, Matsuyoshi, Sawamoto, Fukuyama, & Osaka, 2015), geometrical shapes (Jacobsen, Schubotz, Höfel, & Cramon, 2006), and paintings or musical excerpts (Ishizu & Zeki, 2011) also reflect the extent to which we assign subjective value to stimuli of varying reward properties (see also Brown, Gao, Tisdelle, Eickhoff, & Liotti, 2011; Salimpoor & Zatorre, 2013; Vartanian & Skov, 2014). Moreover, functional connectivity between the nucleus accumbens and vmPFC predicts how much participants are willing to spend on musical excerpts (Salimpoor et al., 2013), suggesting that our evaluative processes can also impact economic choices. These findings suggest that the

brain networks supporting subjective valuation are also implicated in aesthetic judgements, and we will argue below that this involvement extends to creative cognition.

Based on findings from neuroeconomics and studies of preference formation, we can advance a new conceptualization of creativity. Specifically, previous work suggests that two key processes support creative cognition: generation and evaluation of ideas (Basadur et al., 1982; Campbell, 1960; Simonton et al., 1999).[1] Generation involves coming up with many possible solutions or ideas in response to a problem (or prompt), whereas evaluation refers to testing those solutions and ideas and selecting the best option(s) available. Here we posit that these processes also involve assessing the value or utility of ideas in terms of their novelty and usefulness (Diedrich et al., 2015; Runco & Jaeger, 2012; Sternberg, 1999). Thus, the current framework proposes that value-based decision-making processes (e.g., value assignment, representation, comparison) underlie creative cognition.

Conceptualizing creative cognition as value-based decision-making leads to several novel hypotheses. First, it predicts that computations in neuroeconomic valuation regions of the brain (e.g., mPFC, OFC, PCC) should be associated with evaluative processes during creative cognition. Indeed, this prediction has already found support in fMRI studies that explicitly compared generative and evaluative processes during creative cognition. For example, Ellamil, Dobson, Beeman and Christoff (2012) focused on creative drawing, instructing participants in the fMRI scanner to design book covers and to subsequently evaluate their designs and ideas. Compared to the generation of drawings, their evaluation was associated with greater activation in the medial frontal gyrus and PCC, among other regions. In another fMRI study, Mayseless, Aharon-Peretz, and Shamay-Tsoory (2014) demonstrated that evaluating the originality of ideas

[1] Note that we do not make the claim that the generation of ideas is "blind" (see Gabora, 2011).

was associated with activation in a set of regions including the PCC. The results of these two studies are consistent with our predictions, and highlight the role played by neuroeconomic valuation regions during idea evaluation. Another interesting study in this domain was conducted by Hao et al. (2016) who demonstrated that in the context of divergent thinking, engagement in the evaluation of generated ideas compared to a distraction task was associated with higher originality. In addition, electroencephalogram (EEG) recordings indicated that upper alpha activity in frontal cortices was greater during idea generation following evaluation, suggesting that evaluation might "elicit a state of heightened internal attention or top-down activity that facilitates efficient retrieval and integration of internal memory representations" (p. 30). These results suggest that creativity benefits from evaluation, and that fMRI and EEG can be used to examine the localization and dynamics of valuation processes during creative cognition.

Second, because increased fMRI BOLD activity in valuation regions has been associated with increased subjective value (e.g., Kable & Glimcher, 2007), we also predict that neural responses in those regions should correlate positively with the *quality* of ideas (evaluated based on the attributes of novelty and usefulness) generated during creative cognition. For example, when performing divergent thinking tasks such as the alternate uses task, participants' self-reported ratings of originality for their responses should correlate positively with activity in regions such as the mPFC, OFC, and PCC. Finally, given that neural responses in these valuation regions can predict economic choices (Smith, Bernheim, Camerer, & Rangel, 2014; Tusche, Bode, & Haynes, 2010), these neural responses should also predict which idea, out of all the ideas that have been generated, will be selected eventually by the individual as the best idea.

What makes something creative?

Neuroeconomics also seeks to develop computational models that specify which decision variables are computed, how they are computed in distinct brain regions and networks, and how these computations lead to choices (Rangel & Hare, 2010; Ratcliff, Smith, Brown, & McKoon, 2016; Shadlen & Kiani, 2013; Smith & Ratcliff, 2004). These models have proven fruitful in various domains such as perceptual decision making (Churchland, Kiani, & Shadlen, 2008; Gold & Shadlen, 2007), memory (Shadlen & Shohamy, 2016), and self-control (Hare, Camerer, & Rangel, 2009). We believe that they can also be useful in explaining creative cognition.

The assumption underlying most neurocomputational models is that a noisy relative value signal accumulates over time, and that decisions are made once the accumulated information or evidence for one option becomes sufficiently strong to drive choice. For example, a recent study showed that individuals make altruistic or selfish choices by assigning an overall value to each option—computed as the weighted sum of two attributes: reward for self and reward for the other person (Hutcherson, Bushong, & Rangel, 2015). The authors found that the values for these two attributes were computed independently in distinct brain regions before being integrated and represented as an overall value signal in the vmPFC. Given that creative ideas are understood to satisfy the criteria of both novelty and usefulness, in what follows we will outline how neurocomputational models may provide insights regarding attribute integration necessary for the emergence of creative ideas.

The assumptions underlying multi-attribute integration computational models of choice resemble those made in models of aesthetic experiences. Chatterjee and Vartanian (2014, 2016) suggested that distinct neural systems process different aspects of aesthetic experiences (e.g., emotional, perceptual, etc.), and that different weights might be assigned to different systems that underlie those processes. For example, studies have shown that humans prefer curved over

sharp objects (Bar & Neta, 2006), and that sharp objects tend to increase activity in the amygdala (Bar & Neta, 2007), presumably reflecting increased arousal, salience, or sense of threat associated with sharp objects. Neurocomputational models would thus predict that activity in the amygdala might reflect one of the many attributes (e.g., sense of threat) that an individual might take into consideration when computing the overall liking for a sharp or curved object (computed within the brain's reward system). Because creative ideas are also defined along multiple dimensions/attributes (i.e., novelty and usefulness), future work could explore how the values of different attributes are computed and weighed in distinct brain regions, and how their integration causes an individual to evaluate the idea or product high or low on creativity. This proposal is consistent with Martindale's (1984) theory of cognitive hedonics, according to which thoughts (e.g., ideas) have evaluative aspects, which in turn can drive one's preference for and continued pursuit of certain ideas over others. If the common currency hypothesis is correct (e.g., Levy & Glimcher, 2012), then the evaluation of ideas should also occur within the same neural network that computes subjective values for all other stimulus types.

Locus coeruleus-norepinephrine (LC-NE) system supports creative cognition

Exploration and exploitation of ideas

When an idea has high utility (e.g., it is novel and useful), it is often advantageous to exploit the utility the idea provides. In contrast, if an idea has low utility (e.g., it lacks novelty and/or usefulness), it may be preferable to explore other ideas to find better alternatives. Many decisions in our daily lives require us to make a trade-off between exploitation and exploration (Christian & Griffiths, 2016; Cohen, McClure, & Yu, 2007). Do we try new things or stick with existing ones? Which pizza to order? Should you get your "usual" or ask about the specials? Which ideas should one pursue? For example, when inventing a new product, should you

continue developing new ideas after having generated *n* number ideas or should you start to focus on and develop one of them further? The current framework proposes that creative cognition is mediated by processes that resemble those apparent in classic exploitation-exploration dilemmas. In this section, we will outline how activity in the locus coeruleus-norepinephrine (LC-NE) neuromodulatory system might support creative cognition by mediating the transitions between idea exploration and exploitation.

When people are initially trying to find inspiration or ideas for tackling a new problem, they are often attempting to explore and generate ideas that satisfy certain criteria. These criteria may be based on abstract top-down goals that determine how much utility or value is assigned to any particular idea. For example, an artist might be seeking an idea that best conveys a particular meaning or emotion, and a scientist might be developing a new experimental procedure that most stringently tests a theoretical prediction. That is, these individuals are generating ideas by exploring the available options and pruning them by assessing their utilities. Different ideas will have different utilities depending on how well they satisfy certain criteria. Most ideas will likely be entertained very briefly because they fail to satisfy those criteria, and are subsequently discarded. However, when individuals land on an idea that satisfies those criteria sufficiently, they will likely stop exploring additional ideas because they would want to devote their time and resources to fully exploit the utility it provides. The present framework suggests that the creative process described above reflects an adaptive utility-optimization process that is mediated by activity in the LC-NE system and interconnected brain regions that compute and evaluate subjective value.

Locus coeruleus-norepinephrine system and function

The locus coeruleus nucleus sits deep in the pons and sends noradrenergic projections to nearly all brain regions (with the notable exception of the basal ganglia and hypothalamus), and is the only source of norepinephrine to the cerebral, cerebellar, and hippocampal cortices (Foote & Morrison, 1987; Moore & Bloom, 1979) (Figure 2). Because of locus coeruleus' diffuse projections to cortical regions, early research focused primarily on its role in cognitive processes (Amaral & Sinnamon, 1977), especially in mediating arousal (Berridge & Waterhouse, 2003). The LC-NE system's role in regulating cognitive processing and arousal was motivated by the observation that salient and arousing stimuli reliably elicit a *phasic* activation of locus coeruleus neurons and norepinephrine release in cortical target sites (Aston-Jones & Bloom, 1981; Brun, Suaud-Chagny, Gonon, & Buda, 1993; Hervé-Minvielle & Sara, 1995). Phasic activation is defined as a rapid response of short duration (in contrast to tonic activation that evolves more slowly but is of longer duration). Moreover, norepinephrine has also been found to modulate the arousal and gain (i.e., responsiveness) of signals in cortical regions (Devilbiss & Waterhouse, 2000). More recent work suggests that the LC-NE system is also implicated in decision making and utility optimization (Aston-Jones & Cohen, 2005a-b; Aston-Jones & Waterhouse, 2016), which have particularly relevant roles and functions in the present conceptualization of creative cognition.

Early work on creativity and the LC-NE system has already suggested a relationship between noradrenergic activity, arousal, and creativity. For example, early theories of LC-NE function emphasized the system's role in modulating arousal and cognitive processing (e.g., Berridge & Waterhouse, 2003), and early work on creativity demonstrated that low levels of arousal were associated with increased creativity (Martindale & Greenough, 1973). During creative generation, more creative individuals show stronger electroencephalogram (EEG) alpha

band activity (Martindale & Hasenfus, 1978), which is believed to reflect reduced arousal mediated by noradrenergic projections from the locus coeruleus (Foote, Berridge, Adams, & Pineda, 1991; Foote & Morrison, 1987). Moreover, noradrenergic activity has been associated with cognitive flexibility (Heilman, Nadeau, & Beversdorf, 2003; Heilman, 2016; see also Beversdorf, 2013), which is typically measured by tasks that require one to search through a network to identify a solution (e.g., anagrams, compound remote associates task; see Bowden & Jung-Beeman, 2003). For example, studies in rats and humans have shown that reducing noradrenergic activity by administering propranolol (a beta-adrenergic antagonist) improved performance on cognitive flexibility tasks (Alexander, Hillier, Smith, Tivarus, & Beversdorf, 2007; Campbell, Tivarus, Hillier, & Beversdorf, 2008; Hecht, Will, Schachtman, Welby, & Beversdorf, 2014). Although when taken together these findings suggest a link between noradrenergic activity, arousal, and creativity, they have not been integrated into a unified framework.

Phasic vs. tonic locus coeruleus activity drive idea exploration vs. exploitation

The adaptive gain theory of LC-NE function (Aston-Jones & Cohen, 2005b) may provide the necessary insights into the neural processes underlying creative cognition by linking neuroeconomic findings with work relating noradrenergic activity to creativity. According to the adaptive gain theory, LC-NE activity falls on a continuum from phasic to tonic. The present framework suggests that *phasic* locus coeruleus activity is associated with creative processes that exploit or evaluate high-utility ideas (e.g., creative evaluation), whereas *tonic* locus coeruleus activity is associated with processes that involve exploring many potential ideas (e.g., creative generation). In a phasic mode, strong bursts of locus coeruleus activity are tightly coupled with task-related decision processes and indicate that the current task has high utility. Phasic locus

coeruleus activity improves performance and promotes exploitation by filtering irrelevant responses by increasing gain (i.e., responsiveness) of processing and reducing noise in cortical regions (Aston-Jones & Cohen, 2005b; Mather, Clewett, Sakai, & Harley, 2016). In the context of creative cognition, phasic locus coeruleus activity should reflect and promote the exploitation of a high utility idea. In a tonic mode, phasic locus coeruleus activity is reduced or absent but tonic activity is increased; this mode is associated with reduced neural gain, low current task utility, task disengagement, and increased distractibility. During creative cognition, the lack of high utility ideas (e.g., during creative generation) may be associated with the lack of focus on any particular idea and increased tonic locus coeruleus activity, which, in turn, increases baseline norepinephrine release that increases noise in the system to encourage exploration of alternative solutions or ideas (Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999).

Critically, the adaptive gain theory suggests that whether LC-NE activity is in phasic or tonic mode depends on value computations in cortical regions such as the OFC (Padoa-Schioppa & Assad, 2006) and the anterior cingulate cortex (ACC; Heilbronner & Hayden, 2016; Shenhav et al., 2013)— both of which project densely to the locus coeruleus (Aston-Jones & Cohen, 2005a; Porrino & Goldman-Rakic, 1982). Furthermore, during creative cognition, neuroeconomic valuation regions (e.g., OFC) are hypothesized to drive and produce the transitions between phasic and tonic activity in the locus coeruleus. When a newly generated idea is novel and useful, the valuation regions would assign a high utility to this idea, leading to locus coeruleus phasic activity that promotes exploitation of that idea. But when creative ideas are absent, the valuation regions would register low overall utility, sending signals to the locus coeruleus to initiate a shift towards tonic locus coeruleus mode, which would in turn increase baseline norepinephrine release and facilitate exploring and sampling of other ideas that might

provide higher utility. In sum, the subjective value assigned to ideas (determined by how well these ideas satisfy certain criteria) is hypothesized to drive phasic and tonic locus coeruleus activity, which in turn serves to maximize long-term utility by optimizing the trade-off between idea exploitation and exploration.

Reinterpretation of existing findings and new predictions

By extending the adaptive gain theory of LC-NE function to creative cognition, the present framework not only helps to reinterpret and integrate existing findings but also makes new predictions. First, because creative generation is more strongly associated with idea exploration whereas creative evaluation is more strongly associated with idea exploitation, it follows that generation and evaluation should be associated with tonic and phasic locus coeruleus activity, respectively. This prediction can be tested by measuring fMRI BOLD activity in the locus coeruleus (see Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014) during creative generation and evaluation. The P3 event-related potential and pupil diameter have also been shown to correlate with LC-NE activity (Murphy, Robertson, Balsters, & O'Connell, 2011; Nieuwenhuis, Aston-Jones, & Cohen, 2005), with baseline pupil diameter correlating remarkably well with locus coeruleus firing rates, such that larger pupil diameters reflect increased tonic locus coeruleus activity (Aston-Jones & Cohen, 2005b; Rajkowski, Kubiak, & Aston-Jones, 1994). Moreover, exploratory choices during a reinforcement learning gambling task were associated with larger pupil diameter, and changes in pupil size correlated with changes in task utility and the transition between exploitation and exploration (Jepma & Nieuwenhuis, 2011). Given that the present framework proposes that utility computation, exploitation, and exploration processes underlie creative cognition, pupil diameter may provide a useful tool for studying creative processes. These findings further highlight the utility of the present framework because

it proposes several measures (e.g., pupil diameter, locus coeruleus BOLD activity, P3; see also Mather et al., 2017) that can be used to study the processes underlying creative cognition.

Second, since creative people are usually better at generating more and better ideas, the current framework would predict that creative people should have increased levels of tonic or baseline locus coeruleus activity and norepinephrine, which are the neurobiological processes that facilitate idea exploration and generation. Although there is no direct evidence for these individual differences in baseline locus coeruleus activity in relation to creativity, the locus coeruleus has been associated with cognitive function and abilities (Mather & Harley, 2016). Indeed, a recent study found that baseline pupil size (a proxy for locus coeruleus activity) correlates with intelligence (Tsukahara, Harrison, & Engle, 2016), which is a factor that predicts individual differences in creativity (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Jauk, Benedek, Dunst, & Neubauer, 2013; Jauk, Benedek, & Neubauer, 2014; Nusbaum & Silvia, 2011). Thus, the present proposal has the potential to provide an integrative framework that explains not only the bases of creative processes, but also individual differences in creativity.

Third, increased tonic locus coeruleus activity and norepinephrine should predispose creative people to increased distractibility because norepinephrine reduces neural gain and increases noise in the system. These changes suggest that creative people may be more likely to experience sensory overstimulation because of their over-inclusive attention. Consistent with these predictions, many studies have reported that creative people tend to be oversensitive (e.g., Martindale, Anderson, Moore, & West, 1996; Martindale & Armstrong, 1974). Moreover, a recent study found that real-world creative achievement was associated with 'leaky attention' (Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), which was reflected in reduced sensory gating as indexed by the P50 event-related potential. These findings suggest that

real-world creative people might be less able to filter irrelevant information—a filtering process mediated by phasic rather than tonic locus coeruleus activity—and that such leaky sensory gating (mediated by increased tonic locus coeruleus activity) might be one of the processes that benefit creativity by focusing attention on more stimuli regardless of their relevance (Mendelsohn & Griswold, 1964; Russell, 1976). In addition, creative people are often able to connect distantly related concepts or ideas, presumably because increased tonic locus coeruleus activity increases noise and leaky sensory gating, allowing them to make use of more stimuli and cues (Ansburg & Hill, 2003).

Further support for the relationship between tonic locus coeruleus activity and leaky sensory gating comes from recent work showing that pupil diameter reflects locus coeruleus-driven neural gain and sensory processing, such that higher gain (i.e., phasic locus coeruleus activity) was associated with narrow attentional focus whereas lower gain (i.e., tonic locus coeruleus activity) was associated with broader attentional focus (Eldar, Cohen, & Niv, 2013; Eldar, Niv, & Cohen, 2016). Despite the evidence linking increased tonic locus coeruleus activity with creativity, it may also be that creative people are better at switching between the two modes of locus coeruleus activity because creative cognition involves generating *and* evaluating ideas, believed to be mediated by tonic and phasic locus coeruleus activity respectively. Indeed, the mechanisms that determine switching between different modes of cognition in the service of creative problem solving remain one of the major open questions in the area (see Dorfman, Martindale, Gassimova, & Vartanian, 2008; Vartanian, 2009; Vartanian, Martindale, & Kwiatkowski, 2007).

Fourth, the present framework ascribes a central role for the LC-NE system, leading to the prediction that disturbances in the LC-NE system should affect creative cognition. Consistent

with this prediction, the LC-NE system has been implicated in highly overlapping sets of clinical disorders (e.g., schizophrenia, depression, attention deficit disorder, bipolar disorder) associated with either enhanced or impaired creativity (Baas, Nijstad, Boot, & De Dreu, 2016; Kyaga et al., 2011; Simonton, 2014). That is, disturbances in the LC-NE system may affect processes such as sensory gating, utility optimization, and decision making, which, in turn, may be risk factors for clinical disorders and may thus provide an explanatory factor in the link between creativity and clinical disorders.

Valuation processes and LC-NE activity mediate creative cognition network dynamics

Recent neuroimaging work has converged on the view that creative cognition involves dynamic interactions within and between large-scale brain networks, especially the default mode network (DMN) and the executive control network (Beaty, Benedek, Kaufman, & Silvia, 2015; Ellamil et al., 2012; Liu et al., 2015). These findings have led to the idea that the DMN might support creative idea generation, whereas the executive control network modulates activity in the DMN to ensure that task goals are met (Beaty, Benedek, Silvia, & Schacter, 2016). Although these brain networks are clearly implicated in creative cognition, one critical question remains unaddressed: What determines the engagement of these networks, as well as the interactions and transitions between them? The present framework speculates that network dynamics observed during creative cognition are driven by value computations in regions within the brain's valuation system (Figure 1) and activity in the LC-NE system (Figure 2), which optimizes the trade-off between idea exploitation and exploration.

The core brain regions that assign, represent, and evaluate subjective value during value-based decision making are the OFC, vmPFC, and PCC (Bartra et al., 2013; Clithero & Rangel, 2014). Coincidentally, the mPFC and PCC also form the core of the DMN

(Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Zabelina & Andrews-Hanna, 2016), which has been implicated in creative cognition (Beaty et al., 2015, 2016), spontaneous thought (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Mittner, Hawkins, Boekel, & Forstmann, 2016; Smallwood & Schooler, 2015), and internally-oriented cognition such as self-generated thought (Andrews-Hanna, Smallwood, & Spreng, 2014; Zabelina & Andrews-Hanna, 2016). These anatomical and functional overlaps suggest that DMN activity might reflect value-based decision-making processes proposed to underlie creative cognition in the present framework.

Multiple lines of work also suggest that the PCC might play a crucial role during creative cognition. Apart from being implicated in value-based decision making (Bartra et al., 2013; Grueschow et al., 2015) and internally-oriented and creative cognition (Zabelina & Andrews-Hanna, 2016; Christoff et al., 2016), the PCC might mediate functional coupling and transitions between different brain networks. For example, during early phases of divergent thinking, the PCC was strongly coupled with the salience network regions (e.g., insula), whereas during later phases it was coupled with executive control network regions (e.g., dorsal lateral PFC; Beaty et al., 2015). These findings suggest that computations in the PCC might be critical for engaging different brain networks, as well as mediating network interactions and transitions.

Another related possibility is that DMN activity is more closely associated with an exploratory mode of cognition, whereas default suppression is more closely associated with an exploitative mode. In turn, the PCC might mediate shifts between these two modes (Pearson, Hayden, Raghavachari, & Platt, 2009; Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). For example, one study reported increased activity in the PCC during the period leading up to an insightful solution (Kounios et al., 2006). PCC activity during this period might reflect processes

than mediate the shift from exploration (i.e., finding potential solutions) to exploitation (i.e., an insightful solution has been found). Given that the PCC is involved in detecting changes in the environment and mediating subsequent changes in behavior (Pearson et al., 2011), it may be that the PCC plays an important role in detecting changes in the overall utility of ideas during creative cognition, and mediates the shift between different brain networks.

In addition to the DMN and executive control network, the salience network might also play an important role during creative cognition by initiating transitions between brain networks. For example, the PCC shows increased functional coupling with the insular and ACC during initial phases of divergent thinking (Beaty et al., 2015). Critically, the insular and ACC form the core of the salience network, which is believed to play a central role in dynamically coordinating attention and initiating the switch between the default and executive control networks (Cocchi, Zalesky, Fornito, & Mattingley, 2013; Uddin, 2015). During creative cognition, it may be that the salience network facilitates transitions between idea exploration (generation) and exploitation (evaluation).

Importantly, the insular cortex, ACC, OFC, and locus coeruleus nucleus are highly interconnected, suggesting that transitions between LC-NE phasic and tonic activity could be associated with activity in the salience network (ACC and insular cortex). The OFC and ACC send major cortical inputs to the locus coeruleus (Aston-Jones & Cohen, 2005a; Porrino & Goldman-Rakic, 1982); the OFC projects to the insular cortex (Aston-Jones & Cohen, 2005a), which also projects to the OFC and ACC (Aston-Jones & Cohen, 2005a-b). These neuroanatomical interconnections raise the possibility that value computations drive LC-NE activity, which, in turn, mediates interactions and transitions between various brain networks. That is, LC-NE activity might play a central role in governing network dynamics, and this idea is

consistent with the view that the fMRI BOLD signal may reflect neuromodulatory effects more than changes in the spiking rate of neurons (Logothetis, 2008).

The idea that LC-NE activity might drive network dynamics is also consistent with other models of LC-NE function. LC-NE activity has been proposed to facilitate network resetting, such that when the LC-NE system is activated, it resets the system by interrupting existing functional networks and facilitating the emergence of new ones (Bouret & Sara, 2005; Sara, 2009; see also Mittner et al., 2016). For example, it may be that norepinephrine released by the locus coeruleus would reset the attention networks to promote adaptive shifts in attention and changes in behavioral responses (Corbetta, Patel, & Shulman, 2008; Sara & Bouret, 2012). During creative cognition, such attention resetting might facilitate the transition from idea exploration to exploitation. Integrating these theories of LC-NE function is beyond the scope of the current paper, but with the present framework we hope to stimulate future theoretical and empirical work that bridges LC-NE function, creative cognition, and value-based decision making.

Limitations and future directions

By synthesizing ideas and findings from multiple fields, the present framework offers a novel account of creative cognition. However, several issues remain to be addressed. First, this framework assumes that creative cognition is not qualitatively different from normal cognition, in that decision processes that underlie everyday choices are assumed to also support creative processes. However, creative and normal cognition could be seen as mutually exclusive, partially overlapping, or undifferentiated (Abraham, 2013). Clearly, the present framework is incompatible with the mutual exclusivity account, but future work should explore whether the processes underlying creative cognition and economic choice are partially or completely

overlapping. Second, in its current conceptualization, this framework does not distinguish between the various aspects or types of creativity such as divergent thinking, insight problem solving, combination of remote semantic associations, etc. It assumes that the same value-based decision-making processes underlie creative cognition during all of the above, but future work is required to test this assumption. Third, the current framework has the potential to provide an integrative framework that explains not only creative processes within an individual, but also individual differences in creativity. However, more work is needed to test this aspect of the model. Fourth, this paper has discussed creative generation and evaluation as though these two processes occur independently. However, like LC-NE phasic and tonic activity which falls on a continuum, generative and evaluative processes might also fall on a continuum, or it could be that the transitions between these processes might occur too rapidly to be measured using tools that have relatively low temporal resolution (e.g., fMRI). Thus, other neuroimaging methods with greater temporal resolution might be better suited to test some of the framework's predictions.

Conclusion

Recently, several frameworks have been proposed to account for the neural mechanisms that underlie creativity (Boot, Baas, van Gaal, Cools, & De Dreu, 2017; Dietrich & Haider, 2016). Unlike previous accounts, the framework proposed here draws heavily on neuroeconomics to provide an account of how creative cognition occurs in the brain. By thinking about creative cognition as an adaptive value-maximization process supported by activity in the LC-NE neuromodulatory system, it re-conceptualizes the way we think about the creative process and provides a novel perspective that can be used to reinterpret existing findings. Crucially, it offers many new hypotheses, making it testable and falsifiable. Although here we

have outlined some key predictions based on our model, many additional nuanced predictions can be derived from it. Importantly, this framework has the potential to improve our understanding of not just creative cognition, but also the relationship between decision making, neuromodulation, and large-scale brain network dynamics.

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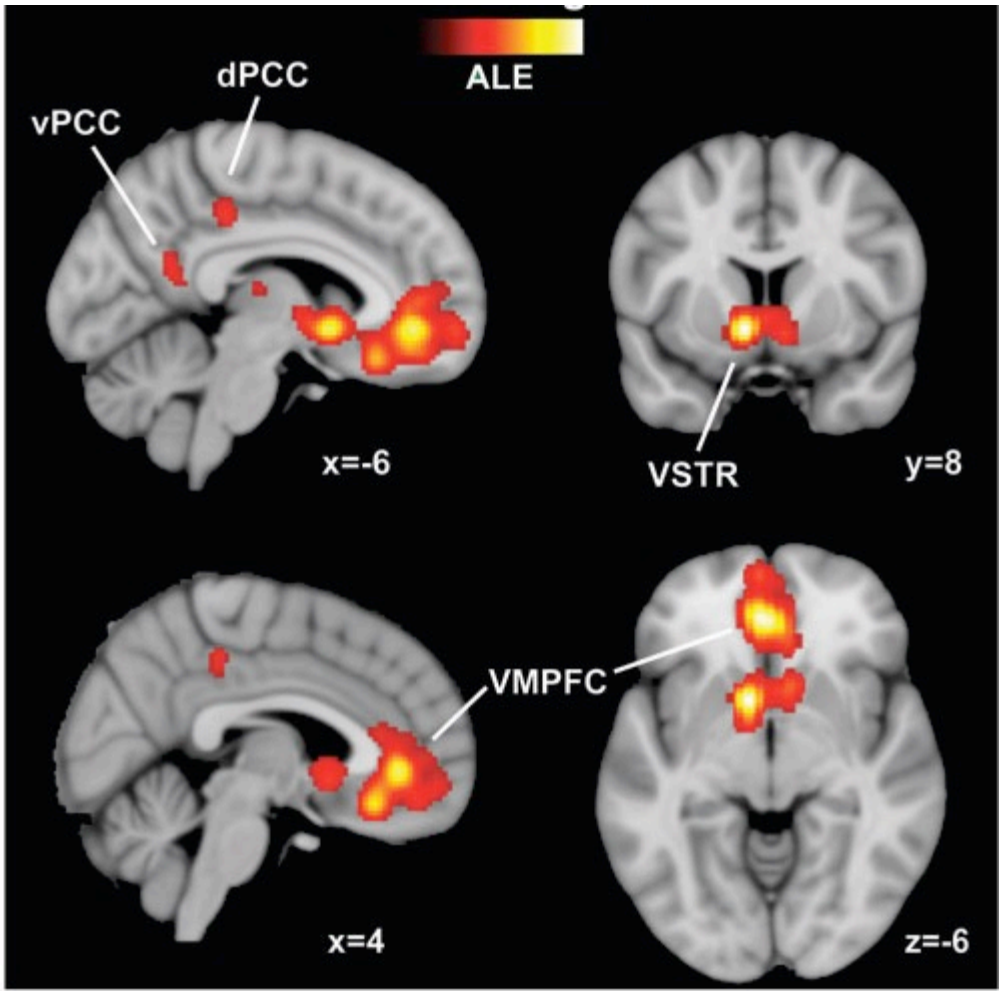

Figure 1. Representation of Value in the Human Brain.

Notes. Regions of the brain that represent value, identified via a meta-analysis of neuroimaging studies. ALE = Activation Likelihood Estimation (brighter regions indicate greater signal strength across studies included in the meta-analysis); dPCC = dorsal posterior cingulate cortex; vPCC = ventral posterior cingulate cortex; VSTR = ventral striatum; VMPFC = ventromedial prefrontal cortex. Reproduced with permission from Clithero and Rangel (2014).

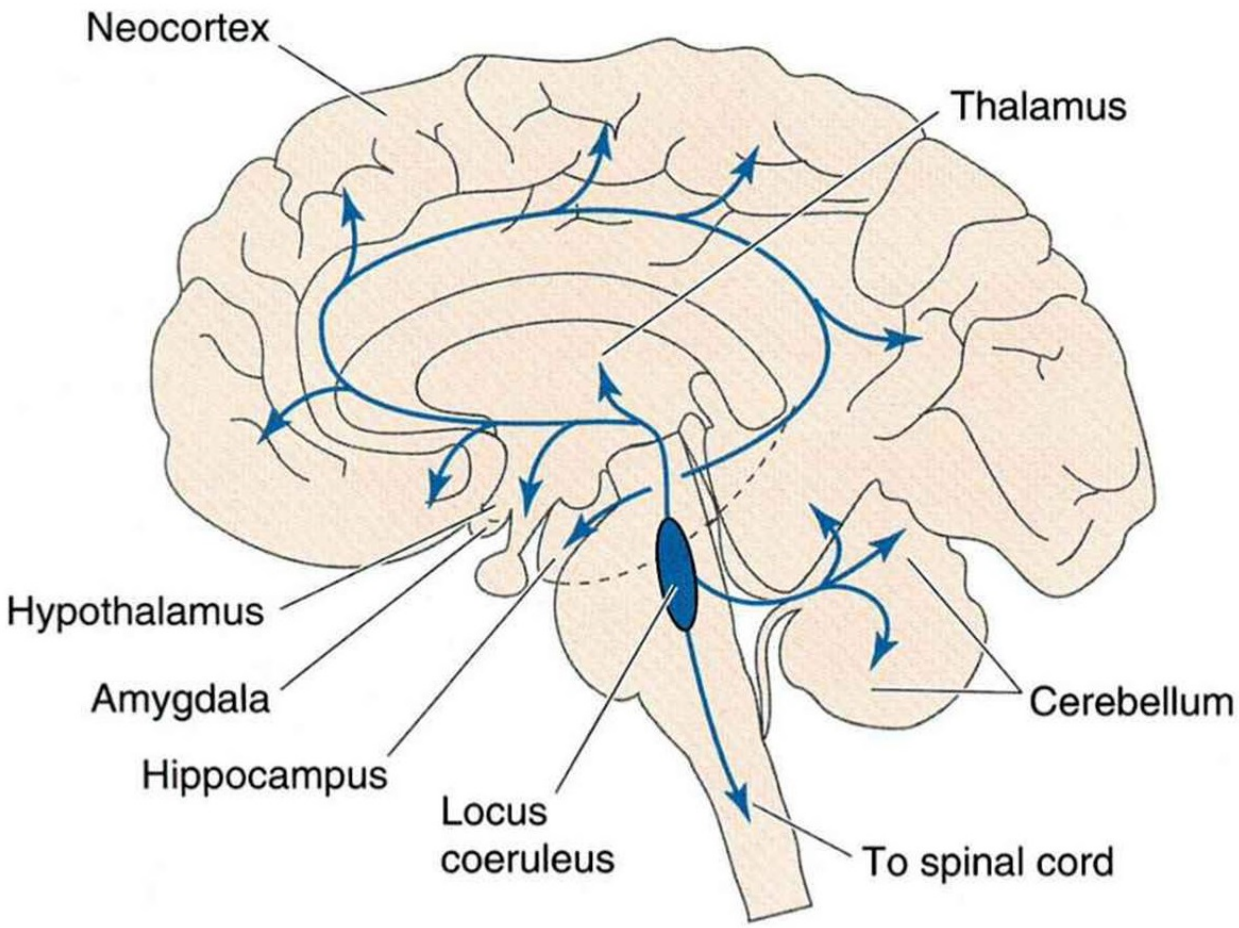

Figure 2. The Locus Coeruleus-Norepinephrine (LC-NE) System.

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