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A Thirst for Knowledge: Grounding Curiosity, Creativity, and Aesthetics in Memory and Reward Neural Systems

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ABSTRACT

Curiosity, creativity, and aesthetics are typically studied separately. The extent to which they share psychological and neural mechanisms is not well understood, despite all being linked to broader personality characteristics like Openness to Experience and are driven by a desire for information and knowledge. Here, we review evidence and advance the hypothesis that creative and aesthetic experiences depend on curiosity as a driver of information-seeking and exploratory behavior because they are exemplars of situations that highlight gaps in knowledge or require problem finding and solving. At the psychological level, we link curiosity, creativity, and aesthetics to Openness to Experience and to ones' semantic memory. We demonstrate how Openness is a critical personality trait in enhancing curious behaviors, as well as creative and aesthetic acts. Furthermore, we highlight the role of semantic memory in such information-seeking behavior, leading to knowledge acquisition. At the neural level, we examine the neurobiological underpinnings of these constructs in relation to the mesolimbic dopaminergic reward system, as related to information-seeking. Finally, we link creativity and aesthetic experience and discuss how stages of art viewing and making relate to curiosity. Thus, we argue that information-seeking, the key behavior attributed to curiosity, motivates both creative and aesthetic activities.

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Introduction

To what extent are curiosity, creativity, and aesthetic experiences related? On the face of it, folk intuitions about these concepts suggest that their connections are obvious: the production of aesthetic objects is itself a creative process; finding a creative solution probably requires some degree of curiosity about what the optimal solution might be; and those who are interested in art (as well as science, travel, nature, etc.) are open and curious about the world. However, although these behaviors appear to share similarities, they are typically studied separately and the extent to which they depend on shared underlying psychological and neural mechanisms is not well understood.

The goal of this paper is to develop a more comprehensive understanding of the relationships between curiosity, creativity, and aesthetics: First, we review empirical evidence supporting the argument that curiosity, creativity, and aesthetics depend on shared psychological and neural mechanisms linked to knowledge, memory and reward. Second, we advance the hypothesis that creative and aesthetic experiences depend on curiosity as a driver of information-seeking and exploratory behavior. Third, we argue that creativity and aesthetic experiences can be understood more fully by considering curiosity because they are exemplars of situations that highlight gaps in knowledge or require exploration to identify problems and solve them.

Examining curiosity, creativity, and aesthetics in isolation can be challenging because researchers often disagree on their exact definitions. Here, we consider curiosity to be a psychological state that represents a desire to know. This state drives behaviors aimed at acquiring new knowledge and experiences (Gross, Zedelius, & Schooler, 2020). We define creativity as the capacity to generate new and useful ideas and products (Runco & Jaeger, 2012); a capacity that often involves making new connections between seemingly disparate domains (Kenett & Faust, 2019; Mednick, 1962). The concept of aesthetics is perhaps the most challenging to define. We operationally define aesthetics as the affective valuations and emotional appraisals of any stimulus such as human faces and bodies, architecture, food, etc. In this paper, we focus primarily on aesthetic experiences involving art, because art objects are a special class of stimuli that are often puzzling and hard to understand. Accordingly, aesthetic experiences of artworks can be deeply influenced by the acquisition of

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knowledge (Chatterjee & Vartanian, 2014) and folk intuitions suggest that curious people are creative and open to aesthetic experiences.

These overlapping notions of novelty and knowledge provide hints as to how curiosity, creativity, and aesthetics relate to each other. Clarifying these links is important given that curiosity, creativity, and aesthetics improve learning, education, productivity, and well-being cross individuals and society (Arnone, Grabowski, & Rynd, 1994; Gruber, Gelman, & Ranganath, 2014; Kashdan & Yuen, 2007; Sakaki, Yagi, & Murayama, 2018). Here, we selectively review the literature regarding these constructs by focusing on curiosity as a driver of information-seeking behaviors. Based on this review, we propose the hypothesis that information-seeking, the key behavior attributed to curiosity, motivates both creative and aesthetic activities.

Curiosity and information seeking

The need to seek information, to find answers, and to pursue knowledge are hallmark characteristics of curiosity. Indeed, many critical scientific discoveries depended on our proclivity to ask “why?” and to *find out* (Hargittai, 2010). The desire to seek information most clearly demarcates curiosity from other psychological constructs and occurs when we become aware of a “knowledge gap” between what we currently know and what information we can potentially acquire (Loewenstein, 1994).

Curiosity is not a monolithic construct (Silvia & Christensen, 2020). It is typically assessed with self-report questionnaires that range from curiosity in social contexts to epistemological needs. For example, two different kinds of motivations can drive the search for information: a drive propelled by pleasure – a positive *liking* of new information; and a drive engendered by feelings of deprivation – a negative *wanting* to receive information to counter a feeling of uncertainty (analogous to FOMO – fear of missing out; Litman, 2005). Deprivation theories situate curiosity as a response to mitigate this latter aversive state. Loewenstein (1994) argues that when confronted with knowledge gaps, humans estimate the magnitude of these gaps based on assumptions about how much knowledge they currently have and how close they are to acquiring the missing knowledge (referred to as *feeling-of-knowing* judgments). Under this view, curiosity represents a tension that paradoxically intensifies as perceived knowledge gaps become smaller and the feeling-of-knowing becomes stronger. That is, we get more curious when we feel closer to acquiring the knowledge we seek (Loewenstein, 1994).

Daniel Berlyne’s influential writings on curiosity over half a century ago remain relevant today. His *optimal arousal* model proposed that humans adjust their behavior to maintain an optimal level of arousal at which they operate best (Berlyne, 1960). According to this model, being under-aroused is an unpleasant, boring state. Animals are motivated to explore and seek novel experiences to increase their arousal. In contrast, exposure to stimuli that are too intense (e.g., highly novel or challenging) over arouse an organism, resulting in avoidance behaviors that reduce arousal back to an optimal level. Curiosity is one motivated state by which people act to increase (seek new experiences) *or* decrease (resolve uncertainty) their arousal to achieve their own internal optimal level.

The types of experience and information that people feel curious about can differ, as can the mode by which they acquire information. For example, Berlyne (1954) located curiosity along two dimensions: a perceptual to epistemic axis and a specific to diversive axis. The first dimension refers to the kind of information being sought. Perceptual curiosity is the desire for new sensory stimulation, while epistemic curiosity is the drive for knowledge and is typically aroused by complex ideas. Berlyne’s insights show that curiosity is directed at acquiring both concrete (e.g., what does this art look like?) and abstract information (e.g., what does this art mean?).

The second dimension refers to the way people seek information. Specific curiosity refers to the pursuit of particular information to close a knowledge gap, whilst diversive curiosity describes a wide-ranging search for the novel. Berlyne’s notions of specific and diversive curiosity received recent empirical support. Lydon-Staley, Zhou, Blevins, Zurn, and Bassett (2021) used computational network science methods to capture styles of curiosity in the behavioral patterns of participants exploring Wikipedia. Knowledge networks were created in which nodes in the network represented unique Wikipedia pages visited and edges reflected the text similarity between the content of different pages. The authors found two styles of information seeking behavior: hunters (who had specific curiosity) and busybodies (who had diversive curiosity). Hunters developed tight knowledge networks by sampling closely related concepts, while busybodies created loose networks by sampling different, sparsely connected concepts. Hunters were sensitive to feeling deprived of information, while busybodies were joyous explorers.

The propensity to seek information as an expression of curiosity is also characterized as a stable personality trait with different dimensions (Silvia & Christensen, 2020). For example, the Five-Dimensional Curiosity

Scale (Kashdan, Disabato, Goodman, & McKnight, 2020; Kashdan et al., 2018) distils curiosity into a multidimensional framework that 1) identifies groups of people who differ along various dimensions and 2) examines how people's personality profiles modulates curious behavior. In line with theories articulated by Berlyne (1954), Loewenstein (1994) and Litman (2008), the dimensions of curiosity described by Kashdan et al. (2020) are *Joyous Exploration* (pleasure in seeking new information), *Deprivation Sensitivity* (aversion to lack of information), *Stress Tolerance* (embrace of doubt arising from new and complex experiences), *Social Curiosity* (interest in other people's thoughts and actions), and *Thrill Seeking* (willingness to take risks and acquire novel experiences). High scores along all of these curiosity dimensions are linked to a greater propensity to seek information.

Creativity and information seeking

For several decades, creativity was considered difficult to study because it seemed inherently elusive (Beaty, Benedek, Silvia, & Schacter, 2016; Glaveanu et al., 2020; Glăveanu & Kaufman, 2020; Kenett et al., 2020; Runco & Jaeger, 2012). While creativity is generally defined as the ability to generate novel and useful ideas, how this ability is realized psychologically and neurally is far from understood. One approach proposes that creativity should be studied in relation to more basic cognitive capacities, such as language, memory, or attention and enduring personality traits (Abraham, 2013, 2014; Benedek & Fink, 2019; Ward, 2007; Ward, Smith, & Finke, 1999). On this approach, researchers try to explain creativity by examining critical components of this multi-faceted construct, such as semantic memory and Openness to Experience (Kenett et al., 2020). Importantly, both memory and Openness also seem to play a critical role in curiosity, thus potentially bridging curiosity and creativity.

Semantic memory is the cognitive system that stores facts and knowledge (Kumar, 2021). Embedded in theories of creativity is the notion that knowledge plays a role in generating creative ideas (Abraham & Bubic, 2015; Kenett, 2018; Kenett & Faust, 2019). The associative theory of creativity describes the role of semantic memory in the creative process (Mednick, 1962). According to this theory, creative thinking involves connecting weakly related concepts in novel and applicable ways: the more distant the concepts are from each other in semantic memory, the more creative the new connection. Furthermore, this theory argues that the semantic memory structure of highly creative people is rich and flexible. Such a structure facilitates deep and broad searches over ones' own memory system (Mednick, 1962), which is analogous to the information seeking behavior that is a hallmark of curiosity, albeit directed internally rather than to the external world. Related to our argument, Hills et al. proposed a general exploration theory (Hills, Todd, & Goldstone, 2007; Hills, Todd, Lazer, Redish, & Couzin, 2015; Todd & Hills, 2020) that argues for a shared mechanism for both external and internal searches.

Computational methods to study knowledge and memory structure in creativity provide empirical support for the associative theory of creativity (Kenett, 2018; Kenett & Faust, 2019). Highly creative people have richer, more connected and less organized semantic memory structures (Benedek et al., 2017; He et al., 2021; Kenett, Anaki, & Faust, 2014; Kenett, Beaty, Silvia, Anaki, & Faust, 2016; Ovando-Tellez et al., 2022), allowing them to search through their memory more easily (Kenett, 2022; Kenett & Austerweil, 2016) and exhibit greater mental flexibility (Kenett et al., 2018). In a recent study, Bieth et al. (2021) applied computational network science methods to empirically examine the impact of solving challenging riddles on how memory might be restructured (see also Durso, Rea, & Dayton, 1994). Memory restructuring (i.e., reinterpretation and reorganization of problem-related representations in ones' semantic memory) is considered to be a cognitive mechanism of insight problem solving (Ohlsson, 1992; Schilling, 2005). Bieth et al. showed that solving riddles successfully related to restructuring of the relations between concepts in solvers' semantic memory relevant to the solution of the riddle. The extent of this restructuring varied in relation to individual differences in creative ability. At the neural level, default and frontal brain regions (Chrysikou, 2019; Marron, Berant, Axelrod, & Faust, 2020) are engaged along with temporal brain region activity in creative processing (Shen, Yuan, Liu, & Luo, 2017) – such as conceptual expansion (the ability to broaden existing conceptual structures in knowledge; Abraham et al., 2012; Abraham, Rutter, Bantin, & Hermann, 2018)

Another major component contributing to creativity is the personality trait of Openness to Experience (Christensen, Kenett, Cotter, Beaty, & Silvia, 2018; Oleynick et al., 2017), which turns out to be a consistent predictor of creative achievement in the arts and sciences (Feist, 1998; Kaufman et al., 2016). Openness to Experience is so strongly linked to creative thought, that some argue that "creativity" could be considered an alternative label for this personality trait (Oleynick et al., 2017). Silvia and Christensen (2020) analyzed a battery of Openness to Experience inventories to examine the relationship of curiosity to various facets of the Openness to Experience trait. They found that facets related to curiosity across the various Openness to Experience inventories were intellect (intellectual curiosity and intellectual interests), aesthetic (aesthetic appreciation), and cultural (non-traditionalism, diversity, and variety-seeking) (Silvia & Christensen, 2020). The authors argue that curiosity is a central component of Openness to Experience, which is linked directly to creativity.

Open people are original, unconventional, imaginative, intellectual, and creative (Christensen et al., 2018; McCrae, 1987). They seek out new experiences and are more sensitive to novelty in experiences that generate interest and evoke pleasure (Fayn, MacCann, Tiliopoulos, & Silvia, 2015). Open people engage in activities that encourage the accumulation of information such as reading different genres of literature for pleasure (Finn, 1997; McManus & Furnham, 2006). In general, Open people are motivated to learn, more likely to explore, and invest effort to acquire different kinds of information (Kashdan, Rose, & Fincham, 2004; Silvia & Sanders, 2010; von Stumm, 2018). Beaty, Kaufman, et al. (2016) show that higher Openness is related to heightened functional connectivity within the default mode network (Beaty et al., 2018). Overall, people high in the trait of Openness to Experience actively acquire information that increases their general semantic knowledge (Christensen et al., 2018), an important component for creative expression.

Aesthetic experiences and information seeking

Finally, we situate aesthetic experience in relation to information seeking. Neuroaesthetics investigates the biological bases of aesthetic experiences (Chatterjee, 2011; Nadal & Pearce, 2011; Skov, Vartanian, Martindale, & Berleant, 2009). These experiences involve appraisals of natural objects, artifacts and environments (Brown, Gao, Tisdelle, Eickhoff, & Liotti, 2011; Coburn et al., 2020) and are common in everyday life. Aesthetic experiences emerge from "the Aesthetic Triad," which involve interactions between sensory-motor, emotion-valuation, and meaning-knowledge neural systems (Chatterjee, 2014; Chatterjee & Vartanian, 2014; Shimamura, 2012).

We can position art objects as a special class of aesthetic stimuli because they embody some of the most extreme experiences captured by these three systems: 1) they can involve highly unusual arrangements of perceptual features that are not otherwise captured in the natural world, 2) they can be experienced as profoundly moving, valuable and rewarding, and 3) they can be highly abstract, intellectually challenging and difficult to understand.

What do we know about the role of knowledge in aesthetic experiences? Kirk et al. (2009) investigated the effects of framing on neural responses. People rated abstract "art-like" images as more attractive if labeled as being from a museum than labeled as generated by a computer. This preference was accompanied by greater neural activity in the medial orbitofrontal and ventromedial prefrontal cortex. Thinking an image was a museum piece also produced activity in the entorhinal cortex, suggesting that people's expectations draw on their memories that enhance (or probably also diminish) visual pleasure. Similarly, Lacey et al. (2011) found that people's ventral striatum and parts of the orbitofrontal cortex were more responsive to the "art status" than to the actual content of visual images. In addition, knowing the title of artworks can facilitate greater engagement with and deepening of aesthetic experiences (Leder, Carbon, & Ripsas, 2006; Millis, 2001). Original artworks are valued more than duplicates (Newman & Bloom, 2012), consistent with our intuitive dislike for forgeries. Huang, Bridge, Kemp, and Parker (2011) found that people have different neural responses when told that they are looking at an authentic or copied Rembrandt portrait. Authentic portraits evoked orbitofrontal activity, whereas copies evoked neural responses in the frontopolar cortex and the right precuneus. EEG evidence suggests that such sensory and contextual integration occurs very rapidly, within 200–300 ms of seeing artworks (Noguchi & Murota, 2013).

The implication of these studies is that context and knowledge beyond the sensory qualities of visual images affects people's neural responses in aesthetic experiences. Education in architecture and design can influence our appreciation of the built environment (Kirk, Skov, Hulme, Christensen, & Zeki, 2009; Vartanian, Navarrete, Palumbo, & Chatterjee, 2021). Knowledge of compositional strategies, stylistic conventions and practices bias viewers' attention to engage with objects aesthetically (Seeley, 2013). For example, people with some exposure to art appreciate abstract art in a way that art-naïve people can find bewildering.

The importance of knowledge and information to aesthetic experiences is exemplified by the way artworks are organized and displayed in museums. Artworks are typically organized categorically according to different time periods, mediums, artists, and themes, which allows visitors to contextualize and make sense of the works they encounter. In addition, text labels provide information linked to each individual work. However, although art museums are often organized in similar ways, not all aesthetic experiences feel alike: whereas some are subtle and fleeting, others can have profound and gripping effects on the person (Cupchik, 2016; Konecni, 2005). Why is that? Consideration of this issue has become increasingly important as empirical aesthetics extends beyond a focus on transient emotions to intense and even transformative aesthetic experiences that many perceivers actively seek.

Leder et al. proposed an information-processing model of aesthetic experience which emerges as a function of information processing along five stages: perception, implicit classification, explicit classification, cognitive mastering and evaluation – ultimately producing aesthetic judgments and emotions as its output (Leder, Belke, Oeberst, & Augustin, 2004). According to this model, depth of processing is a function of the extent to which information is processed in later stages of information-processing. This view shares similarities with Graf and Landwehr's dual-process perspective on fluency-based aesthetics (Graf & Landwehr, 2015). Stimuli can be processed aesthetically using automatic or controlled processes, with the relative contribution of the two systems determining the depth of aesthetic experience. Specifically, processing performed immediately upon encountering an aesthetic object (i.e., Leder et al. perception and implicit classification stages) is bottom-up and stimulus-driven, giving rise to aesthetic evaluations of pleasure or displeasure. In turn, assuming that the stimulus affords it and if there is sufficient motivation on the part of the perceiver, more elaborate top-down processing involving context, meaning, interpretation and understanding can emerge. Such a dual-process model of aesthetics resonates with dual-process models of creativity, that similarly argue that creative thinking is related to bottom-up, spontaneous generation ideas and top-down controlled, evaluation of these ideas (Chrysikou, 2019; Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019; Sowden, Pringle, & Gabora, 2014).

While it is well recognized that knowledge modulates aesthetic experiences, a critical question for the present discussion is how such knowledge is acquired. Some knowledge is acquired passively, whether by listening to a lecture, or from the familial and cultural environments in which a person happens to live. However, active acquisition of knowledge is driven by a desire to learn – the motivational state underlying epistemic curiosity. Similarly, Openness to Experience might also influence how people experience art. Openness is a predictor of positive aesthetic attitudes and predicts visits to museums, reading literature, and art creation and production (McManus & Furnham, 2006) across different cultures (Atari, Afhami, & Mohammadi-Zarghan, 2020). Open people are likely to seek information, are more likely to experience awe (Silvia, Fayn, Nusbaum, & Beaty, 2015) and be sensitive to novelty in artworks (Fayn et al., 2015). We propose that curiosity and its links to Openness are likely major drivers of knowledge acquisition that enriches aesthetic experiences.

Knowledge, memory and executive control

Analogous forms of information-seeking occur in two aspects of creativity: problem finding and problem solving. Problem finding refers to discovering, identifying, and defining problems, and takes place before problem solving begins (Arreola & Reiter-Palmon, 2016; Runco & Nemiro, 1994). For example, exploratory behaviors in which artists engage while preparing to start a new piece of work predict the quality of the artwork they eventually produce (Csikszentmihalyi & Getzels, 1988). On the other hand, as outlined above, solving problems creatively depends on the capacity to make new links between weakly-connected concepts and ideas, and thus depends on searching through one's semantic memory systems (Kenett & Faust, 2019; Mednick, 1962). The importance of information-seeking to both creative problem finding and problem solving generates the hypothesis that curious people are more adept at commandeering their appetite for information into a capacity for creativity.

Similarly, when people confront a challenging or ambiguous piece of art, they recognize a gap in knowledge that keeps them from understanding the art or the intention of the artist. They might be engaged by and enjoy the sensory qualities of the art – its use of color, form and composition – but they also might recognize that there is something they still do not understand about the art. Here, perhaps knowing something about the artist, or the cultural context in which the art was made, or the intent of the artist or analysis by a critic might fill in this gap. Curious people are more likely to seek this information and enrich their aesthetic experience.

Constructs such as specific and diversive curiosity also apply to creativity. This relationship is reflected in the hunter and busybody typology proposed by Lydon-Staley et al. (2021). If hunters form tight knowledge networks made up of closely related concepts, these people would sample closely related ideas when engaging in creative problem solving. However, if creative thinking is facilitated by the ability to make connections between concepts that are distant in semantic memory, then the busybody style of curiosity that is linked to joyful exploration may produce different and more creative outputs and solutions. Indeed, such a busybody personality implies an appetite for varied new information and may thus directly overlap with openness to experience, which facilitates creative thinking.

Epistemic uncertainty is experienced when the recognition of knowledge gaps evokes curiosity, which motivates one to seek information in order to close such gaps and reduce this uncertainty. Similarly, epistemic uncertainty plays a role in creativity and aesthetic experiences. For example, identifying the need for a creative solution to solve a problem, first requires knowing that a gap (similar to a knowledge gap) exists between the current problem and its solution. Further, searching through one's semantic memory in order to make connections between disparate concepts may involve epistemic uncertainty about what the best, most novel, or most applicable solution might be (Jia, Li, & Cao, 2019; Sidi, Torgovitsky, Soibelman, Miron-Spektor, & Ackerman, 2020).

A recent study provides some of the first, direct empirical evidence that creative performance is associated with the extent to which people seek information to resolve epistemic uncertainty (Koutstaal, Kedrick, & Gonzalez-Brito, 2022). Using an innovative curiosity Q&A paradigm, participants were presented with factual sentence stimuli in which certain pieces of information were implicitly missing (e.g. “Alex Bellos was prompted by his public speaking appearances to create an online survey asking people to report their favorite number. After collecting 30,000 responses, there was a clear favorite.”). Participants were then invited to ask questions about the information they received, and their questions were rated for novelty. These questions were categorized as gap-based when they targeted the implicit information gaps in the stimuli (e.g., “What is the most popular favorite number?”), and topic-based when they targeted other, relevant topic information (e.g., “Who is Alex Bellos?”). Finally, participants were given the opportunity to view (or “forage” for) answers to both gap- and topic-based questions. The authors found that the novelty of the questions participants asked correlated with their performance on a *divergent* thinking test of creativity that required the generation of novel solutions. Further, the extent to which participants sought gap-related information in the Q&A task (independent of the novelty of the questions) correlated significantly with their performance on a *convergent* thinking task, which involves finding the correct, optimal solution to a problem. Overall, these results show that active inquiry is a significant predictor of creative thinking (Koutstaal et al., 2022).

Curiosity, as a state that motivates search for meaning, likely plays a role in art appreciation. The artist's choice about what information to communicate and how to do so is likely influenced by curiosity that influences their knowledge of the world (epistemic curiosity) and of the various ways in which their intent might be given physical form (perceptual curiosity). It is not yet known if artists vary on different dimensions of curiosity and how these differences influence their choices of content and style. For example, artists with considerable social curiosity might be more likely to make portraits and social scenes, artists inclined toward joyous exploration might be more likely to produce novel ways of depicting the world, and artists with greater stress tolerance might be more likely to produce emotionally expressive paintings.

With art perception, having preexisting knowledge or expertise perhaps facilitates experiencing curiosity when confronting a new work of art. As described earlier, the feeling of curiosity increases the closer one becomes to acquiring the missing knowledge. Experts may be more curious to discover layers of meaning in works of art because they are confident of their capacity to understand it. Naïve participants may be less likely to engage with complex works of art if they perceive the knowledge gap to be insurmountable. On the other hand, naïve observers who are curious, perhaps those open to experience or those with greater stress tolerance, might be more likely to seek out the meaning of a painting that seems initially inaccessible. The dimensional structure of curiosity might also help explain why people are drawn to certain kinds of art. Mirroring the choices that artists make in production, perhaps viewers with high degrees of social curiosity are drawn to portraits and social scenes, people who are inclined to joyous exploration might be engage more easily with ambiguous and complex art, and people with stress tolerance might be able to immerse themselves in challenging art and emotionally dense imagery.

The role of information and knowledge in curiosity and creativity implicates learning and memory. Curiosity enhances memory for information as it is learned (Duan, Fernández, van Dongen, & Kohn, 2020; Kang et al., 2009; Marvin & Shohamy, 2016; Wade & Kidd, 2019). At the neural level, curiosity is associated with higher activation in the hippocampus and the parahippocampal gyrus (FitzGibbon, Moll, Carboni, Lee, & Dehghani, 2019; Gruber et al., 2014). Moreover, increased hippocampal activity while waiting for the answer to a high-curiosity question and after incorrectly answering a high-curiosity question leads to more accurate recall (Kang et al., 2009). Separately, a large body of work has consistently demonstrated the role of the hippocampus in creativity (Addis, Pan, Musicaro, & Schacter, 2016; Benedek et al., 2014, 2018; Ellamil, Dobson, Beeman, & Christoff, 2012). Creating new ideas recruits very similar brain structures as when one is recalling known solutions (Benedek et al., 2014, 2018). In fact, remembering can be conceived as a (re)constructive process, and the constructive mechanisms involved in episodic recall may also serve the generation of mental simulations about the future and novel ideas (Beaty, Thakral, Madore, Benedek, & Schacter, 2018).

Dopamine signals drive attentional biases toward stimuli associated with past and future rewards ("reward-based salience"; Anderson, 2016; Baranes, Oudeyer, & Gottlieb, 2015). Activity in the ventral striatum and hippocampus elicited by high-curiosity trivia questions predicts better memory for trivia answers (Gruber et al., 2014). Further, individual differences in the activation of SN/VTA and the hippocampus, predicts the magnitude of curiosity-related memory enhancements (Gruber et al., 2014). Consistent with the fact that dopamine enhances hippocampal memory consolidation (Murayama & Kitagami, 2014), curiosity-based memory enhancement for trivia answers occurs even after delays of 1–3 weeks (Fastrich & Murayama, 2020; Kang et al., 2009; Marvin & Shohamy, 2016). In sum, curiosity may improve learning by enhancing attention and consolidating memory, processes mediated by dopamine (Gruber & Ranganath, 2019).

The medial temporal lobe is engaged when memory and knowledge play a role in enhancing aesthetic experiences. For example, Kirk et al. showed that architecture students had greater appreciation for building facades than other students and that this enhanced response was accompanied by greater neural activity in memory related medial temporal structures (Kirk, Skov, Christensen, & Nygaard, 2009).

Both curiosity and creativity involve executive control. For example, curiosity sometimes involves a tradeoff between the ability to deemphasize the demand for immediate reward in favor of indirect benefits of information. Participants in gambling tasks are often willing to sacrifice part of their reward to receive information sooner about the outcome of a gamble – despite the fact that this information does not change their odds of winning (Cervera, Wang, & Hayden, 2020). This process mainly involves classic control brain regions, specifically the dorsal anterior cingulate cortex (dACC). Several theories suggest that dACC monitors exploration, and sends information to downstream neural structures that regulate behavior, such as guiding gaze to salient stimuli (Kolling, Behrens, Wittmann, & Rushworth, 2016; Shenhav, Botvinick, Matthew, & Cohen, Jonathan, 2013). A recent EEG study demonstrated that curiosity about lottery outcomes disinhibits the ACC via the increased amplitude of a "feedback-related negativity" EEG signal that is believed to be related to dopaminergic projections to the ACC (Brydevall, Bennett, Murawski, & Bode, 2018). The ACC was also shown to be responsive to anticipation of information during an observing task in monkeys (White et al., 2019).

Neural mechanisms related to cognitive control are linked to various aspects of the creative process (Beaty et al., 2016, 2018; Beaty, Seli, & Schacter, 2019; Benedek & Fink, 2019; Chrysikou, 2019). Extensive research of brain network connectivity related to creativity consistently reveals that the executive control network and the default network, two large-scale brain networks that typically act antagonistically actually increase functional coupling when a person is thinking creatively (Beaty et al., 2016, 2018, 2019; Benedek & Fink, 2019; Chrysikou, 2019). Since these networks are associated with controlled, evaluative processes and generative, constructive processes, respectively, this connectivity pattern points to a mechanism of how controlled and spontaneous cognitive processes interact more fluidly in creative cognition (Zabelina & Andrews-Hanna, 2016). Finally, brain lesion studies indicate that compromised function of the frontal cortex is typically associated with reduced creative ability, although certain focal lesions or stimulation-induced suppression may also enhance specific aspects of creative cognition (Chrysikou et al., 2013; Kenett, Rosen, Tamez, & Thompson-Schill, 2021; Weinberger, Green, & Chrysikou, 2017).

Predictions and rewards

Creating art may lead to sense of rewarding life fulfillment (Tay, Pawelski, & Keith, 2018). Such a human need for long-term fulfillment may be driven by curiosity and thus tie together these three constructs in relation to activation of the neural reward system. Satisfying curiosity, engaging in creative acts, and having aesthetic experiences are all rewarding. The enhanced learning (Gruber & Ranganath, 2019) driven by curiosity contributes to experiencing reward (Murayama, FitzGibbon, & Sakaki, 2019). The anterior cingulate cortex (ACC) is recruited during states of cognitive conflict aroused by information gaps (Botvinick, Braver, Barch, Carter, & Cohen, 2001). This recruitment occurs especially when people make choices about what information they want to receive (Lau, Ozono, Kuratomi, Komiya, & Murayama, 2020; Oosterwijk, Snoek, Tekoppele, Engelbert, & Scholte, 2020). Appraising one's ability to resolve the gap is linked to neural activity in lateral prefrontal cortex (PFC; Gruber et al., 2014; Jepma, Verdonschot, Van Steenbergen, Rombouts, & Nieuwenhuis, 2012; Kang et al., 2009). This region also provides input to dopaminergic midbrain regions (substantia nigra/ventral tegmental area [SN/VTA]). Dopaminergic neuromodulation originating from SN/VTA enhances exploratory behavior and the motivation to seek rewards, including information (Ballard et al., 2011; Bromberg-Martin & Hikosaka, 2009; Düzel, Bunzeck, Guitart-Masip, & Düzel, 2010). Satisfying curiosity enhances activity in the caudate nucleus and nucleus accumbens (NAcc), consistent with the idea that acquiring information is pleasurable (Gruber et al., 2014; Kang et al., 2009; Ligneul, Mermillod, & Morisseau, 2018). Finally, dopaminergic pathways have been directly implicated in relation to variation in Openness to Experience (DeYoung, 2013, 2015; DeYoung, Peterson, & Higgins, 2005; Käckenmester, Bott, & Wacker, 2019; Smillie et al., 2021). For example, a recent study demonstrated how the effect of a dopamine blocker sulpiride on a creativity task interacts with individual differences in Openness to Experience (Käckenmester et al., 2019)

Kang et al. reported activation in the striatum when participants anticipated the answer to a trivia question about which they were curious (Kang et al., 2009) Since then, several studies have reported activation in the midbrain and striatum during anticipation for information in different tasks such as trivia, lottery, and observing (Charpentier, Bromberg-Martin, & Sharot, 2018; Gruber et al., 2014; Kobayashi & Hsu, 2019). These studies support the idea that curiosity scaffolds the brain's reward regions to drive information-seeking behavior (i.e., behavior that reduces uncertainty about the world; Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006; Hikosaka, Bromberg-Martin, Hong, & Matsumoto, 2008).

Dopamine is also implicated a in creative thinking (Chermahini & Hommel, 2010; De Manzano, Cervenka, Karabanov, Farde, & Ullen, 2010; Mayseless, Uzefovsky, Shalev, Ebstein, & Shamay-Tsoory, 2013; Oh, Chesebrough, Erickson, Zhang, & Kounios, 2020; Schuler et al., 2019; Tik et al., 2018; Zabelina, Colzato, Beeman, & Hommel, 2016). For example, Mayseless et al. (2013) showed that a specific genetic marker of dopamine receptors (the DRD5-7 R allele) relates to lower performance in standard creativity tasks. Conducting a ultra-high magnetic field MRI study while participants performed insight problem-solving tasks, Tik et al. (2018) examined the neural correlates of the insight (Aha!) moment – the subjective feeling of relief that occurs when the solution to a problem suddenly emerges into conscious awareness. Subcortical activity changes were associated with these Aha!-moments in the dopaminergic midbrain (VTA, nucleus accumbens and caudate nucleus) and in the bilateral thalamus and hippocampus. Thus, one could hypothesize that the rewarding feeling of relief that occurs when one's curiosity is satisfied is similar to the pleasure one feels when a problem is solved insightfully.

The brain's reward systems are also integral to aesthetic experiences, especially when considering beauty (Brielmann & Dayan, 2022; Van de Cruys & Wagemans, 2011). The pleasure that people derive from looking at beautiful objects taps into our reward circuitry (Kühn & Gallinat, 2012). For example, attractive faces activate the fusiform face area (Chatterjee, Thomas, Smith, & Aguirre, 2009) and parts of the ventral striatum (Kim, Adolphs, O'Doherty, & Shimojo, 2007) even when people are not thinking explicitly about the attractiveness of these faces. The orbito- and medial-frontal cortex, the ventral striatum, anterior cingulate and insula respond to beautiful visual images (Jacobs, Renken, & Cornelissen, 2012; Jacobsen, Schubotz, Höfel, & Cramon, 2006; Vartanian & Goel, 2004) and the medial orbitofrontal cortex and adjacent cingulate cortex respond to different sources of pleasures including music (Ishizu & Zeki, 2011) and even architectural spaces (Vartanian et al., 2013).

Beyond the immediate hedonic experience of satisfying curiosity, being creative, and being immersed in aesthetic experiences, the anticipation and predictions of rewards also plays an important role. These processes can be framed within a reinforcement learning perspective that focuses on error prediction, monitoring, and novelty seeking – via dopaminergic pathways (Iigaya et al., 2020; Montague, Dayan, & Sejnowski, 1996; Morris et al., 2016; Wittmann, Daw, Seymour, & Dolan, 2008). A prediction error account suggests that the brain actively generates representations of the world based on past experience and predicts future events based on such a representation (Bar, 2007; Kesner, 2014). On this account as related to aesthetic experiences such as viewing art (Christensen, Cardillo, & Chatterjee, in press), a mismatch between the sensory information of the viewed piece of art with its conceptual representation can produce a prediction error that propagates across the brain. Such a sensory-conceptual mismatch may lead to an effort to minimize the error by engaging in information-seeking curious behaviors (Kesner, 2014; Van de Cruys & Wagemans, 2011). The striatum has a mediating role in the coding and valuation of prediction error (Pagnoni, Zink, Montague, & Berns, 2002; Schultz, Dayan, & Montague, 1997). The propagation of errors from the sensory-motor (i.e., thalamus) and emotion-valuation (i.e., striatum) systems to the meaning-making system may represent the positive (curiosity) or negative (confusion) minimization of the mismatch between sensory input and previous experience (Kesner, 2014; Van de Cruys et al., 2014).

A call to empirically investigate the curiosity-creativity-aesthetics link

While many theoretical discussions link curiosity to creativity and innovation, empirical evidence directly supporting this link is scarce (Gross et al., 2020; Schutte & Malouff, 2020). Research on each respective construct points to mechanistic links, as we have tried to outline, but more research is needed to establish these links. Are perceptual and epistemic curiosity underscored by the same attentional and motivational processes? Are these same processes implemented in the expression of visual and verbal creativity, or scientific and artistic creativity?

Gross et al. (2020) highlight specific gaps regarding the link between curiosity and creativity. Specifically, the authors identify methodological limits and scarcity in behavioral and experimental measures of curiosity. The authors argue that these limits minimize the ability to directly and empirically investigate the relation and potential overlap between curiosity and creativity. For example, the relation between epistemic and perceptual curiosity to creative behavior and performance have been supported only by correlational observations (Gross et al., 2020). However, curiosity is currently receiving renewed attention in psychology, and recent studies are beginning to offer new and innovative ways of studying it experimentally. For example, the study by Lydon-Staley et al. (2021) offers an example of how curiosity can be studied empirically in an ecologically valid setting (browsing Wikipedia). In addition, the Curiosity Q&A study by Koutstaal et al. (2022) provides an innovative paradigm to investigate curiosity empirically that can be adapted to investigate the roles of question-asking and information-seeking in many domains. Future research in this area must clarify the links between curiosity, creativity and aesthetics more explicitly, and these very recent studies offer new methods by which this might be achieved. For example, it may be possible to adapt the Wikipedia study by Lydon-Staley et al. to examine how people explore art museum spaces (real or virtual). Is it possible to identify "hunters" who seek specific information from text labels to understand a particular artist or movement, and "busybodies" who explore museum spaces more freely and attend to whatever captures their attention? Characterizing aesthetically-relevant information seeking makes it possible to explicitly test the hypothesis that art is experienced as more beautiful when you receive information that allows you to better understand it.

Further, in the Koustaal (2022) study, the Curiosity Q&A task and the creativity tasks they used were completely unrelated. However, it is possible to adapt this paradigm to test the curiosity-creativity link more directly. For example, participants could be presented with limited information about a problem, given the opportunity to ask questions and seek information to deepen their understanding of the problem space, and then asked to generate a creative solution to the problem. Such a task could be designed to explicitly test the hypothesis that the extent to which people seek information about a problem significantly predicts their ability to creatively solve it.

Overall, to truly uncover the link between curiosity, creativity, and aesthetics, research needs to move beyond correlational research based on self-reports toward experimental research using manipulations and interventions, capturing these three constructs together. For example, research that manipulates low and high levels of information seeking could examine its impact on creative aesthetic products. Similarly, while we review the similar role of the brains' reward system across these three constructs, no neurocognitive study that we know of has directly examined the role of the reward system in these three constructs at the same time. Finally, given the role of attention in driving information seeking, intervention studies via brain stimulation paradigms can examine the impact of exciting or inhibiting the inferior frontal gyrus (implicated in cognitive control; Chrysikou, Weber, & Thompson-Schill, 2014), on information seeking when developing creative aesthetic products. Several studies have shown how brain stimulation over that region can indeed enhance or inhibit the originality of creative responses (Chrysikou et al., 2013; Chrysikou, Morrow, Flohrschutz, & Denney, 2021; Kenett et al., 2021). Thus, such research should also be conducted in curiosity and aesthetic experiences.

Conclusions – curiosity drives creativity and aesthetic experiences

Our brief review of curiosity, creativity, and neuroaesthetics, generates the hypothesis that curiosity drives creativity and aesthetic experiences in several ways. Personality traits that predispose curious people overlap with the propensity to also be creative and be open to aesthetic experiences. We propose that curiosity is a critical driver of creativity and aesthetic experiences. More specifically, we argue that curiosity facilitates the creative problem-finding process in the early stages of the creative process and drives exploratory meaning-making processes during the problem-solving stage.

Furthermore, we argue that curiosity influences aesthetic experiences because it motivates behaviors toward understanding stimuli that are complex, abstract, and intellectually challenging. Central to this hypothesis is the role of meaning and knowledge – our semantic memory system. Curiosity drives the acquisition of information in order to close gaps between what is known and not known. This acquisition occurs in different ways and is driven by different motivations. The drive varies by personality traits, and the same traits that make people curious predispose people to creative acts and aesthetic engagements. Indeed, semantic memory has been argued to be the scaffolding of imagination and creativity (Abraham & Bubic, 2015), and we extend this argument to aesthetic experiences. The central role of information-seeking in curiosity may underpin the ability to find and solve problems in creative ways by allowing one to seek new connections between disparate concepts within one's own semantic memory system. Furthermore, relieving curiosity, enjoying works of art, and finding creative solutions all engage the brains' reward system in a similar way by evoking a subjective feeling of relief, satisfaction, pleasure, or "aha" moments. Overall, knowledge – stored in semantic memory – offers a rich platform upon which creativity can operate in concert with other systems such as attention and learning. The same semantic memory deepens our aesthetic experiences to penetrate beyond superficial appraisals of objects and artwork.

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