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A shared novelty-seeking basis for creativity and curiosity

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Abstract

Curiosity and creativity are central pillars of human growth and invention. Although they have been studied extensively in isolation, the relationship between them has not yet been established. We propose that both curiosity and creativity emanate from the same mechanism of novelty seeking. We first present a synthesis showing that curiosity and creativity are affected similarly by a number of key cognitive faculties such as memory, cognitive control, attention, and reward. We then review empirical evidence from neuroscience research, indicating that the same brain regions are involved in both curiosity and creativity, focusing on the interplay between three major brain networks: the default mode network, the salience network, and the executive control network. After substantiating the link between curiosity and creativity, we propose a novelty-seeking model (NSM) that underlies them and suggests that the manifestation of the NSM is governed by one's state of mind.

1. Introduction

Curiosity and creativity are considered fundamental drives in human behavior (e.g., Boden, 2004; Kobayashi, Ravaioli, Baranès, Woodford, & Gottlieb, 2019). Curiosity has been defined in the past as a motivation to explore uncertain environments (Li et al., 2019; Litman, 2005), and as a state by which one is rewarded by new knowledge and novel experiences (Kashdan & Silvia, 2009; Litman & Jimerson, 2004; Litman & Spielberger, 2003). According to the classical definition of Berlyne (1966), curiosity is "the condition of discomfort due to an inadequacy of information that motivates specific exploration" (p. 26). Others referred to curiosity as a natural exploratory process aimed at gaining new information (Tian, Silva, & Liu, 2021), which is thought to induce other essential behaviors for exploring novel, surprising, or intriguingly complex stimuli (Kidd & Hayden, 2015). These different definitions all converge to seeing curiosity as a state by which one seeks novelty.

As to creativity, it has been operationalized in the past as an active behavior and as a personal trait, and in both contexts, it has been consensually defined as the creation, or ability to create something that is both novel and useful (Runco & Acar, 2012; Sternberg & Lubart, 1996). To delineate our discussion within existing research, here we predominantly focus on curiosity as a state and on creativity as a behavior or action and their underlying cognitive processes, as they are controllably operationalized and measured in a lab, in hope that the theoretical framework proposed here may apply to curiosity and creativity "in the wild."

The crux of our proposal is that curiosity and creativity converge on novelty-seeking mechanisms, whereby curiosity is a novelty-seeking state in which we more readily attend and absorb novelty in the world, screening what will eventually be learned and consolidated, in creativity we seek novel recombinations of stored knowledge. Within this framework, we further propose that because curiosity facilitates attention, categorization, and consolidation of new information, it serves creativity, which uses stored representations in memory to generate novel ones.

Curiosity has been conceptually associated with creativity in the past (Day & Langevin, 1969; Maw & Maw, 1970), and several empirical studies have investigated this potential relationship. These studies indicated a positive correlation between curiosity and creativity measures in adults (Hardy, Ness, & Mecca, 2017; Vidler & Karan, 1975), high school students (Karwowski, 2012), and children (Rubenstein, 2000). Hagtvedt, Dossinger, Harrison, and Huang (2019) provided an initial demonstration of a predictive link between curiosity and creativity by showing that inducing curiosity increased creativity score in a subsequent idea generation task, supporting the possibility of a causal link between the two. Similarly, a recent small-scale meta-analysis of 10 studies concluded that there was a positive correlation between self-reported curiosity and both self-reported and rated creativity (Schutte & Malouff, 2019). Thus, although curiosity and creativity are typically studied separately, these few reports provide initial support to the link between them.

In this article, we link curiosity and creativity by showing the covariations and reciprocal interactions between them in diverse contexts and conditions. After substantiating this link, we propose a novelty-seeking model (NSM) that underlies them. Finally, we show how one's state of mind (SoM; Herz, Baror, & Bar, 2020) determines the manifestation of novelty seeking.

2. The cognitive underpinning of curiosity and creativity

Curiosity and creativity are complex cognitive constructs that involve several psychological mechanisms and brain networks. In this section, we show how curiosity and creativity act similarly across multiple domains, reflecting their proposed connection. We focus on aspects such as openness to experience and to uncertainty, as well as on key functions of human cognition such as attention, memory, and cognitive control – all of which were found to be involved in curiosity and creativity, independently and in a similar way. To account for these dynamics, we follow the SoM framework (Herz et al., 2020) as a global concept. This framework proposes that the mind is a multidimensional construct that changes according to circumstances, influencing our subjective experience of the environment. To explain how the dynamics of different dimensions relate to one another, the SoM framework suggests that dimensions change along a continuum ranging from narrow to broad. Broad thinking entails broad perception, global attention, exploratory behavior, and positive mood. Conversely, narrow thinking entails narrowed perception, local attention, exploitatory behavior, and negative mood. We suggest that the global SoM and its related dimensions exert coordinated effects on curiosity and creativity, most directly facilitated by an exploratory SoM. Hereafter, we aim to integrate the literature from both domains to support the unified nature of curiosity and creativity. It should be noted that despite our efforts to allocate equal attention to curiosity and creativity, empirical research in the field of curiosity has remained relatively scarce in comparison to the extensive body of research on creativity. That said, we posit that the integration of literature on curiosity and creativity presented herein has the potential to yield reciprocal advantages and catalyze advancements in both domains.

2.1 Openness to experience

The SoM dimension most relevant for the understanding of curiosity and creativity is openness to experience, which determines the way we approach novel information. Openness to experience is traditionally considered to be a personality trait, part of the "big five" model of personality structure (Digman, 1997), which is tightly related to both curiosity (Silvia & Christensen, 2020; Silvia & Sanders, 2010) and creativity (Beaty & Silvia, 2012; Li et al., 2015; McCrae, 1996). Openness to experience is the most consistent personality predictor of different forms of creativity: creative thought (Puryear, Kettler, & Rinn, 2017), self-perception (Karwowski & Lebuda, 2016), activity (Batey & Furnham, 2006), and achievement (Feist, 1998). At the same time, curiosity is a central component of openness to experience, which represents a core attribute of the trait (Silvia & Christensen, 2020).

According to the SoM framework, beyond being a personality trait, openness to experience is also a dynamic *state* along the exploration/exploitation continuum, and whether we explore or exploit depends on the specific current context (Herz et al., 2020). In an exploratory SoM, people attend the environment with a wider scope, are more learning-oriented, and are attuned more to sensory input than to familiar knowledge in memory (Herz et al., 2020; Hills et al., 2015). This mode has been shown to increase the likelihood of making a thought breakthrough (Andriopoulos & Lewis, 2009). On the other hand, in an exploitatory SoM, people rely more on what they already know and on *a priori* expectations, less open to novelty and surprises, and gravitate more to the details than to the "big picture" (Schwartenbeck, FitzGerald, Dolan, & Friston, 2013). Interestingly, it has been further suggested that novelty seeking is affected by the tension between exploration and exploitation, such that increased exploitation reduces the chance for novel responses in a free associations task (Baror & Bar, 2016).

An exploratory orientation enables the acquisition of new knowledge and identification of novel associations between concepts (Acar & van den Ende, 2016; Baror & Bar, 2016), which are required for both curiosity and creativity. Curiosity has been conceptualized in the past as an exploratory decision-making strategy, in which the choice made is not associated with any external rewards (Davis, Settlage, & Harlow, 2012; Harlow, Harlow, & Meyer, 1950; Kidd & Hayden, 2015). This relationship was further suggested to be bidirectional, such that higher levels of interest in an activity, which indicate curiosity, predict in turn exploratory actions (Berlyne, 1966; Kashdan & Silvia, 2009).

Exploration has also been found to be involved in creative thinking (Carroll, 2011; Picciuto & Carruthers, 2014), creative problem solving (Ruscio & Amabile, 1999), and improvisation (Martín, Ric, & Hristovski, 2015). Exploration was argued to favor creativity by facilitating the sampling of different stimuli (Laureiro-Martínez, Brusoni, & Zollo, 2010), eventually increasing the repertoire of possible responses, thus enhancing novel thoughts and actions (Blikstein, Silveira Gomes, Teruo Akiba, & Schneider, 2017). Similarly, demand for exploration was argued to increase as the desire for originality increases (Madjar, Greenberg, & Chen, 2011), further linking originality with exploration. In that sense, considering that creativity requires both originality and usefulness, it seems that exploration is especially associated with the "novel" and "original" rather than "useful" component in creativity. This point is further exemplified in recent work by Steele, Hardy, Day, Watts, and Mumford (2021) who examined whether exploration and exploitation are related to creativity in different ways. The authors found that although exploration was positively related to the novelty of the product, exploitation was related to the usefulness of the product.

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Exploitatory behavior was argued to promote monitoring, control, and persistence (Steele et al., 2021), allowing one's performance to be evaluated and refined (Ford, Weissbein, Smith, Gully, & Salas, 1998). More specifically, according to reinforcement learning models, although exploration enables a wider search for a greater range of information, the narrower search in exploitation is more efficient and takes full advantage of existing information (Harada, 2020). Along similar lines, Ruscio and Amabile (1999) gave participants a novel structure-building task: Half of them received heuristic instructions for the task that aimed to increase exploratory behavior, and the other half received algorithmic instructions (a step-by-step demonstration for building a sample structure) that aimed to increase exploitatory behavior. The heuristic instructions led to a flexible experimentation with the task materials, as well as a tendency to use learned techniques in a less rigid fashion. Interestingly, participants receiving the algorithmic instructions exhibited greater confidence and speed during the task, but they were less likely to engage in exploratory behavior or to deviate from the sample structure. These results further demonstrate the different contribution of exploration and exploitation to the creative process. Both exploration and exploitation appear to be necessary for creativity, but their corresponding contribution is exerted at different phases of the creative process (Harada, 2020).

One should take into account that exploration and exploitation strategies present trade-offs (Lavie, Stettner, & Tushman, 2010; March, 1991), which must be managed during the process (Andriopoulos & Lewis, 2009). Throughout acts of creativity or curiosity, people alternate between an exploratory SoM, which is necessary for novelty seeking, and an exploitatory SoM, which is necessary for further refinement and elaboration (March, 1991; Mehlhorn et al., 2015). In creativity, exploration enables generating original ideas, whereas exploitation is needed for further elaboration and evaluation. A similar process may take place in curiosity. Curiosity is typically identified with exploration of the environment for novelty, but exploitation may be needed for selecting what information to gather for further learning and consolidation. Although the dynamic of the shifts between exploration and exploitation requires further investigation, it seems that both creativity and curiosity rely on the intricate balance between exploration and exploitation (Herz et al., 2020; Schad, Lewis, Raisch, & Smith, 2016; Smith & Lewis, 2011).

Clearly, openness to experience is not dependent solely on the balance between exploration and exploitation. It is rather a multidimensional construct (Christensen, Kenett, Cotter, Beaty, & Silvia, 2018; Silvia & Christensen, 2020), and some of its facets (such as the need of novelty; Joy, 2004; Lynn & Snyder, 2002) might even mediate the link between curiosity and creativity.

2.2 Tolerance for uncertainty

Uncertain environments provide significant amounts of new information. As human beings, we seek a sense of certainty, which helps us plan and be prepared for the future (i.e., exploitation SoM). At other times and states (exploration SoM; see Herz et al., 2020, for a review), we are tolerant for surprises and seek novelty.

Research has suggested that curiosity facilitates information seeking and interest in the unknown, despite perceived potential negative consequences (Hsee & Ruan, 2016; Kashdan & Silvia, 2009). In a similar fashion, curious individuals are more likely to see problems as challenges to be solved rather than as insurmountable setbacks (Denneson, Smolenski, Bush, & Dobscha, 2017). Thus, although some may attempt to minimize uncertainty by refraining from novelty altogether, the state of curiosity, almost by definition, serves as a mechanism for minimizing uncertainty by approaching new knowledge – a notion supported by recent studies (Blanchard, Hayden, & Bromberg-Martin, 2015; van Lieshout, Vandenbroucke, Müller, Cools, & de Lange, 2018, 2019). In this fashion, curiosity might serve as an approach–avoidance regulatory function (Kashdan & Silvia, 2009), influencing one's tendency to withstand or engage in certain activities based on an uncertainty appraisal. The avoidance system constrains the breadth of attention (Derryberry & Tucker, 1994; Friedman & Förster, 2010), and the approach system promotes broad associative thought (Chermahini & Hommel, 2012). Because curiosity is associated with increased exploration, it may sustain an approach orientation (Gasper & Middlewood, 2014), ultimately increasing the probability to engage in creative activities (e.g., de Dreu, Nijstad, & Baas, 2010; Flaherty, 2005; Friedman & Förster, 2010; Jauk, 2019) that relate to novelty seeking and openness to experience as well (Baas, Nijstad, Koen, Boot, & de Dreu, 2020).

Interestingly, curiosity is associated with being more comfortable with anxiety (Kashdan et al., 2013), allowing risk-taking behavior, which has long been acknowledged as integral to creativity (Dewett, 2007; Eisenman, 2013; Feist, 1998; Runco, 2015; Simpson Steele, 2015; Sternberg & Lubart, 1992). Taking sensible risks was postulated to be a prerequisite for creativity, as it promotes breakthroughs and innovativeness (Baas, Koch, Nijstad, & de Dreu, 2015; Sternberg & Lubart, 1992), further linking uncertainty with exploration and novelty in creativity. Similarly, uncertainty was found to enhance the generation of ideas (Audia & Goncalo, 2007), whereas avoiding uncertainty may restrain individuals from generating novel ideas (Erez & Nouri, 2010). More directly, Mueller, Melwani, and Goncalo (2012) found that having high tolerance for uncertainty was associated with greater chances of recognizing a creative idea, compared with having low tolerance for uncertainty. Together, it is not unlikely that curiosity, which is considered a state in which uncertainty-related anxiety is reduced, may ultimately result in enhancing creativity. Specifically, curiosity may help transforming situations of uncertainty from being experienced as threatening to provide a fruitful ground for the generation of novel ideas.

2.3 Attention to the novel

Curiosity and creativity are both tightly and reciprocally linked to the scope of attention. In some sense, curiosity directs our attentional "spotlight" toward what we perceive as potentially interesting (Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Kidd & Hayden, 2015). In creativity, similar attentional processes take place, broadly considering representations that would potentially facilitate a novel combination (Benedek, 2018; Chun, Golomb, & Turk-Browne, 2010). Here we propose that curiosity and creativity rely on shared attentional mechanisms. Supporting this notion, Gross, Araujo, Zedelius, and Schooler (2019) recently demonstrated that both curiosity and creativity are characterized by exploratory eye movements. Curiosity was associated with faster anticipatory gaze shifts to the expected location of the answer in trivia tasks (Baranes, Oudeyer, & Gottlieb, 2015), and wider saccadic exploration of visual scenes was associated with trait curiosity (Risko, Anderson, Lanthier, & Kingstone, 2012). The level of curiosity was even predicted by gaze patterns using machine learning methods (Baranes et al., 2015).

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Although the link between curiosity and attention is quite clear, in creativity this link is more complex, because of the two-stage conceptualization of creativity that begins with broad idea generation and concludes with a narrow selection based on usefulness or appropriateness. Creativity was found to relate to different types of attention such as broad attentional scope (Ansburg & Hill, 2003), focused attention (Nusbaum & Silvia, 2011), "leaky" or defocused attention, that is, attention that allows "irrelevant" information to be noticed (Carson, Higgins, & Peterson, 2003; Martindale, 1999; Mendelsohn & Griswold, 1964; Rawlings, 1985), and flexible attention, that is, the ability to switch between focused and defocused attention (Vartanian, Martindale, & Kwiatkowski, 2007; Zabelina & Robinson, 2010). Defocused attention enables some information to "leak in," whereas focused attention is needed to screen out interfering stimulation for further elaboration (Benedek, 2018). Similarly to how both exploration and exploitation contribute to creativity at different stages, attentional processes seem to show a similar two-phase dynamic influence on creativity. As proposed above, we suggest that curiosity predominantly shares the broad attentional scope with the first stage of idea generation in creativity.

Notably, previous studies suggested that individuals with attention-deficit/hyperactivity disorder (ADHD) are more creative (White & Shah, 2006, 2016). As ADHD is associated with leaky attention and with distraction by irrelevant stimuli (Baird et al., 2012; Carson et al., 2003; Zabelina, Saporta, & Beeman, 2016), the question is how the attentional scope of individuals with ADHD relates to their curiosity (Kidd & Hayden, 2015). It is challenging for individuals with ADHD to stay focused and to withhold their response because their likelihood of being attracted by task-irrelevant stimuli is higher. These attentional fluctuations and leaky attention may subserve the link between curiosity and creativity in general. For instance, a certain degree of distractibility was found to improve flexibility in the generation of ideas (Baird et al., 2012; Carson et al., 2003), and processing of irrelevant stimuli was suggested to expand the associative network, resulting in original combinations of information (Boot, Nevicka, & Baas, 2017). It was suggested that although leaky attention per se may result is some forms of attention disorders and/or psychopathology, high cognitive control would serve as a protective factor, and together with leaky attention, would support creative achievements (Zabelina, 2018). In other words, what may seem an attentional deficit of pathological distractibility may in fact subserve curiosity by allowing attention to be directed to possibly irrelevant yet novel information, and creativity as well if subsequent cognitive control is then applied to narrow the scope of attention toward a creative achievement (Zabelina, 2018).

2.4 Memory consolidation

Here we propose that creativity and curiosity are further linked through their parallel interaction with memory consolidation. Research shows that curiosity has an influence on consolidation and category-clustering processes. Induced curiosity seems to enhance memory performance (Kang et al., 2009), and people who are highly open to experience and curious show more efficient recall abilities, and generate more associative responses (Christensen et al., 2018; Gruber, Gelman, & Ranganath, 2014; Kang et al., 2009). Similarly, with regard to creativity, Beaty and Kenett (2020) suggested that individuals who are high in openness to experience have a richer and more interconnected semantic memory. Thus, it seems that by increasing the chance to notice novel information that might be overlooked or coded as irrelevant by others (i.e., defocused attention; Zabelina, 2018, or diffused attention), curiosity and openness to experience also support richer consolidation processes. The increased interconnectedness can later subserve creativity, when attempting to generate novel ideas from existing knowledge, in promoting richer and broader associations. For example, it was found that creative writers showcase the ability to use richer sets of representations in a given context (Andreasen & Powers, 1975). These findings are in line with the SoM framework, according to which exploration is interlinked to a broad scope of associative thinking, attention, and perception.

Although curiosity improves memory of novel information, creativity intimately relies on the reorganization of existing knowledge (Lewis, Knoblich, & Poe, 2018) and involves goal-directed memory retrieval (Madore, Thakral, Beaty, Addis, & Schacter, 2019). Previous studies demonstrated that original ideas usually emerge from combining distal domains of knowledge (Miron-Spektor, Gino, & Argote, 2011; Mumford, Baughman, Supinski, & Maher, 1996; Simonton, 2003). Furthermore, it was suggested that novel ideas do not emerge *ex nihilo* but are thought to arise from meaningful variations and recombination of available knowledge (Campbell, 1960). Studies show that during creative tasks, like many other mental activities, task-relevant information is derived from long-term memory (Beaty, Benedek, Silvia, & Schacter, 2016a; Benedek et al., 2014a). Interestingly, the induction of episodic memory (i.e., brief training in recalling details of a recent event) prior to beginning a creativity task was found to enhance creative performance (Madore, Addis, & Schacter, 2015).

In the same vein, according to the associative theory of creativity (Mednick, 1962), the specific structure of semantic memory, characterized by "flat" (broader associations) instead of "steep" (few, common associations) associational hierarchies, is necessary for accessing remote concepts and weaker connections. The more remote these concepts are, the more creative the new combination will be. In line with this theory, recent network-science studies (e.g., Baronchelli, Ferrer-i-Cancho, Pastor-Satorras, Chater, & Christiansen, 2013; Karuza, Thompson-Schill, & Bassett, 2016) suggested that for highly creative people, more distant concepts appear closer in their associative networks. These studies demonstrated that associative networks marked by shorter path lengths and increased interconnectivity between concepts tend to characterize creative thinkers (Benedek et al., 2017; Gray et al., 2019; Kenett, Anaki, & Faust, 2014). The short path lengths indicate a faster diffusion of information and smaller distances between concepts with fewer mediating associations (Li, Kenett, Hu, & Beaty, 2021). Successful consolidation of interlinks in memory, as curiosity seems to promote, would enable connecting nodes in a novel manner and the shortening of path lengths in the network, eventually resulting in a more efficient and flexible network (Kenett, 2018). It is important to note here that although research has predominantly focused on semantic networks, it is likely that episodic memory is involved as well (e.g., Madore et al., 2015, 2019). More specifically, Duszkiewicz, McNamara, Takeuchi, and Genzel (2019) suggested that although novel experiences that share some commonality with past ones ("common novelty") promote semantic memory formation via systems memory consolidation, experiences that bear only a minimal relationship to past experiences ("distinct novelty") trigger strong initial memory consolidation in the hippocampus, resulting in vivid and long-lasting episodic memories. Curiosity may alter the way episodic experiences are encoded, ultimately changing the way these memories are accessible for subsequent creative combinations.

To conclude, we propose that curiosity influences memory encoding in a way that critically facilitates access to memory during creativity. We further propose that the relationship between curiosity/creativity and memory is bidirectional: Curiosity boosts consolidation of novel information and results in more interconnected memories, and the more interconnected the memory is, the higher the probability of the creative process to occur. A further function for this relationship is associative flexibility (Benedek, Könen, & Neubauer, 2012b), which uses control processes to shift between contexts and concepts in memory, and reach more distinct and remote networks (Marron et al., 2018), as we describe next.

2.5 Cognitive control: Balancing competing demands

Creativity and curiosity are complex cognitive constructs comprised of competing demands, tensions, and trade-offs. As mentioned above, both contain elements that seem at odds with one another, such as exploration–exploitation, focused–defocused attention, and originality–usefulness, which must be simultaneously accommodated during the process (Lewis, 2000). To manage these inherent tensions, both curiosity and creativity employ cognitive control processes (Benedek & Fink, 2019; Cervera, Wang, & Hayden, 2020; Chrysikou, 2018, 2019), which include updating the content in working memory, shifting between tasks and mental sets, and inhibition functions (Miyake & Friedman, 2012). These functions allow performance to be optimized through dynamic adjustments in attention allocation, response selection, and maintenance of task-related goals (Botvinick, Carter, Braver, Barch, & Cohen, 2001).

Studies show that executive abilities optimize both creativity (Beaty & Silvia, 2012; Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014b) and curiosity (Foley, Kelly, Mhatre, Lopes, & Gottlieb, 2017; Lau, Ozono, Kuratomi, Komiya, & Murayama, 2020). For example, high working-memory capacity was found to promote the fluency and originality components of creativity by supporting goal maintenance (de Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012). In line with that, highly creative participants showed higher attentional flexibility by engaging more cognitive control during the attentional switch (Zabelina & Ganis, 2018). Shifting was suggested to allow management of the trade-off between competing interests during curiosity tasks (Cervera et al., 2020) and the selection and implementation of more effective task strategies during creativity tasks (Beaty & Silvia, 2012; Benedek, Franz, Heene, & Neubauer, 2012a). Interestingly, task switching has recently been found to enhance both divergent and convergent forms of creative thinking, by reducing cognitive fixation, which is characterized by the inability to shift away from an undesired thought or idea (Lu, Akinola, & Mason, 2017).

Inhibitory control might benefit both creativity and curiosity by facilitating the suppression of interference from common and inappropriate response tendencies, as was documented in creativity research (Beaty & Silvia, 2012; Benedek et al., 2012a; Chrysikou, 2019), and by deemphasizing the demand for immediate reward in favor of indirect benefits of information, as was suggested in curiosity research (Cervera et al., 2020). Thus, although not yet investigated directly, inhibitory control might suppress affinity to the mundane when surveying our environment curiously similarly to the suppression of mundane ideas in creativity.

In addition to steering and optimization, cognitive control plays a special role in creativity as it is responsible for the evaluation and appraisal of the novelty and usefulness of stimuli and ideas in context, prioritizing information that is task relevant (Chrysikou, 2019). An increasing number of studies hold that the evaluation phase plays an important role in the creative process (for a review, see Kleinmintz, Ivancovsky, & Shamay-Tsoory, 2019). For example, Benedek et al. (2016) tested participants' evaluation accuracy in differentiating between common, inappropriate, and creative ideas, and found that accuracy was positively correlated with creative skills.

Some behavioral studies have highlighted the importance of evaluation processes in curiosity as well, suggesting that curiosity relies on the appraisal of one's ability and resources to resolve the challenges raised by the recognition of an information gap (Noordewier & van Dijk, 2016; Silvia, 2005, 2006). In the context of curiosity, evaluation refers to novelty appraisal (including incongruity, complexity, unexpectedness, obscurity, and uncertainty; Berlyne, 1960). This is followed by an evaluation of coping potential, such as a person's ability to comprehend a new, complex stimulus (Scherer, 2001; Silvia, 2005). Therefore, stimuli evaluated as novel, yet potentially comprehensible, are experienced as interesting. When evaluation determines that the information is worth pursuing, it is proposed to reinforce the novelty seeking by coupling this information with signals from the dopaminergic system (Lau et al., 2020), a reward mechanism that is further detailed in the next section.

In summary, flexible regulation, supported by cognitive control mechanisms(Hommel, 2015), seems to be crucial for both creativity and curiosity. It allows optimizing performance by managing the multiple tensions that creativity and curiosity are wrought of, as well as alternating between competing strategies. Moreover, cognitive control plays an important role in evaluating stimuli and ideas during the curious/creative process, selecting which information to focus on in curiosity, and which ideas are appropriate in creativity.

2.6 Motivation and reward: The novelty-seeking drive

Although for task-related behaviors the goal of a task is known in advance and can be quantified in terms of extrinsic rewards, the motivation for curiosity (Loewenstein, 1994; Oudeyer, Kaplan, & Hafner, 2007) and creativity (Grant & Berry, 2011; Joy, 2004; Kaufman & Beghetto, 2009) seems to be predominantly intrinsic. Intrinsic motivation reflects an interest in and enjoyment of an activity for the sake of the activity itself, rather than for its instrumental value (Deci, 1971; Ryan & Deci, 2000). One innate motivation for such a strategy is the brain's information-seeking drive that intrinsically urges organisms to explore their environments (Anselme, 2010; Bromberg-Martin & Hikosaka, 2011). It has been suggested that knowledge itself might act as an intrinsic reward (Brydevall, Bennett, Murawski, & Bode, 2018; Charpentier & O'Doherty, 2018; Ligneul, Mermillod, & Morisseau, 2018). Generating creative ideas, just as acquiring novel information, or satisfying our drive to learn something new, activates the reward system and is characterized by an increase in dopamine levels (Takeuchi et al., 2010). It is therefore possible that high levels of dopamine, which is thought to be the "neuromodulator of exploration," lower the behavioral threshold for engagement in creative activities (Jauk, 2019) and in information seeking (Bromberg-Martin & Hikosaka, 2009; Gottlieb, Lopes, & Oudeyer, 2016; Redgrave, Gurney, & Reynolds, 2008).

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To explain such behaviors and the high degree of motivation associated with them, it seems necessary to assume that the brain generates intrinsic rewards related to learning or acquiring information (Berlyne, 1960; Gottlieb et al., 2013). Studies show that external rewards are not necessary to elicit curiosity-driven behavior, as reward-related dopaminergic circuits can be activated by information independently of extrinsic rewards. For example, human infants naturally explore new environments regardless of physical rewards (Berlyne & Slater, 1957; Kreitler, Zigler, & Kreitler, 1984).

Indeed, higher curiosity has been associated with increased activation of reward regions in the brain (Gruber et al., 2014; Jepma, Verdonschot, van Steenbergen, Rombouts, & Nieuwenhuis, 2012; Kang et al., 2009; van Lieshout et al., 2018). Similarly, increased activation of reward regions was also documented during creative problem solving (e.g., Oh, Chesebrough, Erickson, Zhang, & Kounios, 2020), and dopaminergic medications were found to enhance divergent thinking among Parkinson's patients (Faust-Socher et al., 2014; Garcia-Ruiz, Castrillo, & Desojo, 2019). Associations between dopamine levels and creativity were also reported to have a genetic basis (Murphy, Runco, Acar, & Reiter-Palmon, 2013). In line with this, studies show that novel information induces dopamine release in the hippocampus, triggering memory consolidation and boosting memory persistence (Duszkiewicz et al., 2019; Tulving & Kroll, 1995; Wittmann, Bunzeck, Dolan, & Düzel, 2007). It is therefore not unlikely that curiosity as well as creative thinking trigger reward-related neural changes.

Although the positive impact of intrinsic motivation on creativity and curiosity has been highlighted, extrinsic motivation, whenever an activity is performed to attain some separable outcome (Ryan & Deci, 2000), has been less investigated in this context (Amabile, 1995; Anderson, Potočnik, & Zhou, 2014). Nevertheless, given the tensions curiosity and creativity bear, aiming to fill an information gap or seeking a solution to a specific problem both might also involve extrinsic motivation. For example, curiosity was suggested to involve both the intrinsic pleasure of learning as well as extrinsically regulated concerns about the accuracy or fit of newly gathered information (Ryan & Deci, 2000). Extrinsic motivation has an incremental effect on creativity as well, especially when the reward is contingent on creativity (Eisenberger, Pierce, & Cameron, 1999; Eisenberger & Rhoades, 2001). It is reasonable to assume that intrinsic and extrinsic motivation could synergistically benefit creativity and curiosity. Intrinsic motivation may be essential for the novelty component (Amabile, 1993), just like exploratory SoM, whereas extrinsic motivation can help to ensure perseverance and elaboration, similar to exploitatory SoM.

We suggest that the underlying motivation of curiosity and creativity is novelty seeking, and just like the satisfaction of basic biological needs such as thirst or hunger, the hunger for knowledge (or novelty) is satisfying (Biederman & Vessel, 2006; Lau et al., 2020; Murayama, 2022). From an evolutionary perspective, rewarding curiosity and creativity may be a long-term investment. Unlike the satisfaction of biological needs, here, the brain invests resources in satisfying mental needs that might turn out to be profitable in the future (Oh et al., 2020).

To summarize, thus far we provided a body of evidence suggesting that shared cognitive mechanisms may link curiosity and creativity. We demonstrated how both are tightly related to SoM and are governed by dynamic trade-offs between exploration and exploitation, which are flexibly tuned by cognitive control. We further demonstrated how curiosity and creativity and their reinforcing dynamics are related to memory and attention. Finally, we postulated that both are driven by a shared entity of novelty seeking.

3. The neuroscience of curiosity and creativity

In this section, we review empirical evidence from neuroscience research, indicating that shared brain regions are involved in both creativity and curiosity. We first discuss dual-process models of human cognition and the role of spontaneous and controlled processes in creativity and curiosity. Then we focus on three major brain networks: the default mode network (DMN), the executive control network (ECN), and the salience network (SN), and their role in curiosity and creativity. Finally, we integrate existing findings to propose modes of interplay between these three networks.

3.1 Spontaneous and controlled processes

What are the processes that may induce us to become curious about a certain stimulus? How are creative ideas generated in our mind? One of the oldest and most ubiquitous approaches in the effort to understand thinking is to distinguish two types of processes that together comprise the broader sphere of cognition (Barr, Beaty, & Seli, 2020). Dual-process models of cognition assume two modes of cognitive processing, which are typically named type 1 and type 2 thinking processes (e.g., Evans, 2007; Stanovich, 1999). Type 1 processes are described as automatic, rapid, effortless, nonconscious, and associative in nature, in which a stimulus (either external or internal) elicits associations to relevant information in long-term memory (Benedek & Jauk, 2018). Type 2 processes are described as controlled, analytic, slow, conscious, and effortful, and are related to working-memory processing (Kahneman, 2011).

Other models classify thinking as either spontaneous or controlled (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). Spontaneous cognition (also referred to as undirected or self-generated thinking; Christoff, 2012) can be defined as thinking processes that are stimulus-independent or are non-deliberative and less prone to conscious guidance. This mode involves rapid information retrieval from episodic and semantic memory that is mostly unconscious (Sowden, Pringle, & Gabora, 2015) and is typically linked to the DMN (e.g., Fox & Christoff, 2014). On the other hand, controlled cognition (also referred to as goal-directed thought), refers to thoughts that are stimulus-driven or deliberative and is guided by top-down processes (Marron & Faust, 2019), is typically ascribed to the ECN (e.g., Seeley et al., 2008). This mode requires cognitive control for maintaining task focus, developing mental strategies, task monitoring, and evaluating outcomes (Benedek & Jauk, 2018; Chrysikou, 2019).

Dual-process models have a long tradition in creativity research (for a recent review, see Sowden et al., 2015), yet these models are lacking in curiosity research. Traditionally, creativity is depicted by a two-staged process (Basadur, 1995; Martindale, 1999; Mayseless, Aharon-Peretz, & Shamay-Tsoory, 2014; Sowden et al., 2015): the generation phase, where a combination of remote associations is activated in a novel manner, and a subsequent evaluation phase, in which ideas are logically valued. Spontaneous and controlled processes are associated with generative and evaluative functions, respectively, which are thought to interact in the forging of creative ideas (Benedek & Jauk,

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2018). In line with this, Guilford (1956) originally distinguished between convergent and divergent thinking, whereby although divergent thinking underlies the generation phase, convergent thinking guides goal-directed reasoning and related mental operations, and involves enhanced evaluative processes (see Zhang, Sjoerds, & Hommel, 2020 for the different neurocognitive mehcanisms involved in each).

Theoretical accounts of creative cognition, hence, acknowledge the relevance of both spontaneous and controlled processes, which can be loosely mapped to the conceptualizations of type 1 and type 2 thinking, or undirected and goal-directed thought (Benedek & Jauk, 2018). Accordingly, we suggest that curiosity can be conceptualized using similar terms: We propose that curiosity first begins with divergent and spontaneous exploration of novel information in a nonrestrictive manner, just like we spontaneously generate as many ideas as we can in creativity. Subsequently, a more controlled selection is activated, guided by our estimation of relevance and interest, resulting in convergence to a certain stimulus to be examined more closely and possibly stored in memory. We propose that spontaneous and controlled modes of cognitive processing, mediated by DMN and ECN, underlie the trade-offs between exploration and exploitation and between defocused and focused attention, respectively, interchanging during the processes of curiosity and creativity. We further postulate that the dynamic shift between the networks is governed by the SN, which functions as a switchboard. Evidence for the involvement of these brain networks in creative thought and curiosity is reviewed next.

3.2 DMN: The initiation of novelty seeking

What are the neural mechanisms and dynamics driving affinity toward the novel? We suggest that novelty detection or generation is triggered by expectancy violation and involve spontaneous thoughts that are manifested by novel neuronal firing. In other words, novel ideas and new information elicit a neural activity pattern that has never occurred before and results in a cascade of neural responses across the novelty network (Kafkas & Montaldi, 2018; Murty, Ballard, Macduffie, Krebs, & Adcock, 2013). This unique pattern precedes the initiation of curiosity and creativity and is manifested by a slow uprising phase of a spontaneous fluctuation in cortico-hippocampal circuits. This is followed by low-level activation spread in relevant networks generated by any new content (Noy et al., 2015) and ends with dopamine release in the hippocampus (Duszkiewicz et al., 2019; Wittmann et al., 2007).

Slow anticipatory buildup of spontaneous fluctuations, also previously known as "readiness potential" (Kornhuber & Deecke, 1965), has recently been suggested as the driving mechanism of the entire range of voluntary behaviors (Moutard, Dehaene, & Malach, 2015) and more specifically was observed prior to creative idea generation (Broday-Dvir & Malach, 2021). When such a fluctuation crosses the activation threshold, a spontaneous mental event can emerge (Norman, Raccah, Liu, Parvizi, & Malach, 2021). Using this account, being in a novelty-seeking mode raises the neural activity above the decision threshold and explains how certain stimulation can attract our attention and be perceived as novel and interesting. Thus, we suggest that large-scale ongoing spontaneous (also termed resting state) activity throughout the cortex plays a role in novelty detection.

The primary neural network that has been suggested to sustain both spontaneous thought (Andrews-Hanna, Smallwood, & Spreng, 2014; Beaty et al., 2016a; Buckner, Andrews-Hanna, & Schacter, 2008; Jung, Mead, Carrasco, & Flores, 2013; Raichle et al., 2001) and associative and predictive processing (Bar, Aminoff, Mason, & Fenske, 2007; Stawarczyk, Bezdek, & Zacks, 2021) is the default mode network (DMN). The DMN includes the medial prefrontal cortex (mPFC), the posterior cingulate cortex (PCC/precuneus), and the bilateral inferior parietal lobes (IPL; Gusnard & Raichle, 2001). These areas have been reported to be involved in information integration (Binder, Desai, Graves, & Conant, 2009), memory retrieval (Ciaramelli, Grady, & Moscovitch, 2008; Sugiura, Shah, Zilles, & Fink, 2005), mind-wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007), generation of associative predictions (Bar et al., 2007; Baror, Aminoff, & Bar, 2021), and bottom-up processing (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). The DMN demonstrates increased activation during a resting state (Gusnard & Raichle, 2001) and is thought to support cognitive processes that draw upon stored episodic or semantic knowledge (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010), such as the generation of novel conceptual combinations (Volle, 2018; Zabelina & Andrews-Hanna, 2016). Thus, the DMN constitutes a plausible candidate for mediating novelty-seeking initiation.

Indeed, activation of key regions of the DMN was repeatedly found during the generation of creative ideas (e.g., Beaty et al., 2014, 2016a; Gonen-Yaacovi et al., 2013; Ivancovsky, Kleinmintz, Lee, Kurman, & Shamay-Tsoory, 2018; Jung et al., 2013; Mayseless, Eran, & Shamay-Tsoory, 2015). Furthermore, activation of the DMN, together with the hippocampus, is thought to be involved in the production of novel combinations of associations (Bar et al., 2007; Beaty et al., 2016a; Bendetowicz, Urbanski, Aichelburg, Levy, & Volle, 2017; Madore et al., 2019). Although less investigated, several neuroimaging studies point to the involvement of the DMN in curiosity as well (Li et al., 2019). For example, van Lieshout et al. (2018) found that curiosity was related to increased activity in the IPL. In line with our hypothesis, it was suggested that during curious state, prior knowledge and novel information are integrated by the mPFC (Ligneul et al., 2018). Further exploration of the involvement of the DMN in curiosity may be fruitful in unlocking the neural correlates of curiosity, illuminating the neural circumstances associated with the state of being curious in which novel knowledge is more readily obtained.

Interestingly, associations between DMN and openness to experience were found in several studies (e.g., Adelstein et al., 2011; Beaty et al., 2016b; DeYoung, 2015). For example, Beaty et al. (2016b) demonstrated that openness predicts increased DMN efficiency, which is thought to reliably measure the network integrity, and considered to reflect efficiency in information processing in the network. In this context, the ability to engage the neurocognitive resources of the DMN efficiently may account for the tendency of highly open individuals to be drawn to novel stimuli. Taken together, we propose that the initiation of creativity and curiosity is manifested by a spontaneous activity in networks such as the DMN which is later evolve to a unique neural firing in subsequent networks.

3.3 SN: Evaluation and selection of new information

After attending to the novel, we evaluate the relevance of the detected novel information. The evaluation of potential relevance does not directly map onto cognitive control but is rather a

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complex process that also relies on valance-valuation judgments ascribed to the SN (Kleinmintz et al., 2019). The SN includes the bilateral anterior cingulate cortex (ACC) and the anterior insula (AN), which are associated with assigning valance to relevant stimuli (Uddin, 2015). The SN has close connections with regions involved in emotion and motivation, such as the amygdala, the ventral tegmental area (VTA), and the caudate (Menon, 2015). Thus, the SN is thought to determine whether the stimulus will be approached or avoided, and what emotional valance is associated with it (Barford, Fayn, Silvia, & Smillie, 2018; Chrysikou, 2018; Xia, Touroutoglou, Quigley, Feldman Barrett, & Dickerson, 2017). It has been suggested that fronto-insular nodes function as iterative "relevance detectors" of both external and internal information (perceptual and episodic information, respectively), which if deemed relevant becomes available in working memory for ECN processing (Chrysikou, 2018). Therefore, the SN may contribute to the detection of relevant stimuli (Uddin, 2015) within the DMN, such as candidate ideas in creativity (Jung et al., 2013) and novel information in curiosity (Li et al., 2019).

Induction of curiosity was found to activate the AN and the ACC (Jepma et al., 2012). Insular activity was also found to relate to curiosity relief (i.e., the sense that curiosity was satisfied), as activity there seems to increase linearly with the amount of information gained after curiosity was satisfied with the desired information (van Lieshout et al., 2018). The insula is also engaged in various creative processes, such as creative idea production, divergent thinking, and visual creativity (Beaty, Benedek, Barry Kaufman, & Silvia, 2015; Wu et al., 2015). For example, increased gray matter volume in the insula was suggested to be associated with higher creativity (Takeuchi et al., 2010).

Considering that both curiosity and creativity seem to be driven by novelty, we suggest that the SN determines the threshold for them to be triggered. Similar to the perception of signals and in line with the signal detection theory in psychophysics (e.g., Peterson, Birdsall, & Fox, 1954; Tanner & Swets, 1954), it is possible that the more curious and creative you are, the higher your sensitivity to novel stimuli would be; thus, more candidate information will cross the threshold for further elaboration. We suggest here that SN activity regulates the threshold for novelty detection.

3.4 ECN: Top-down monitoring and evaluation of novelty

It has been suggested that actions that are associated with new information require control, whereas actions that have low uncertainty are habitual and can be performed with little control-related resources (Cavanagh & Frank, 2014; Fan, 2014). Under this claim, curiosity and creativity, which both involve engagement with novelty, are predicted to require controlled processing. The ECN is a vast, frontal network known to involve several control-related processes. For example, inhibition is mediated by the ventro-lateral prefrontal cortex (vlPFC, also known as the inferior frontal gyrus; IFG), working memory is mediated by the dorsolateral prefrontal cortex (dlPFC), error detection is related to the medial prefrontal cortex (mPFC), updating is associated with the temporoparietal junction (TPJ), and switching involves the interaction between several fronto-parietal regions (Chrysikou, 2018, 2019; Kleinmintz et al., 2019). It was further suggested that increased ECN activity can support response combination and selection by evaluating the novelty of the generated responses (Chrysikou, 2019). Interestingly, during evaluation of novelty, higher activations were found in the ECN, as opposed to evaluation of appropriateness, in which increased activity was found in regions related to memory, emotion, and motivation (Huang, Tang, Sun, & Luo, 2018), suggesting that evaluation of novelty is related to cognitive control processes, whereas the evaluation of appropriateness may be related to different mechanisms (Sowden et al., 2015).

Curiosity might also involve regions associated with information evaluation required to accomplish its functions (Tian et al., 2021). Indeed, some initial evidence demonstrates how the ECN might play a role in curiosity as well. Kang et al. (2009) found that activity in the caudate and in the IFG during a trivia task was associated with self-reported curiosity. The key analyses focused on activations during the anticipatory period after participants had received a question, but before they were given the answer. The anticipatory period parallels the evaluation phase to some degree, as participants had to assign a value to the question and evaluate their interest in finding out the answer.

The involvement of cognitive control in creativity is studied to a greater extent than the involvement of cognitive control in curiosity but its role is debatable. Neuroscientific evidence contributes to this ongoing discussion. Activation across regions in the ECN was found during various types of creative thought such as divergent thinking tasks, musical improvisation, and creative problem solving (Chen, Beaty, & Qiu, 2020; Jung et al., 2013; Perchtold et al., 2018). Overall, ECN recruitment appears to be a function of whether creative cognition is constrained to meet task-specific goals (Beaty et al., 2016a). For example, it was found that under conditions of high semantic constraints, in which one is primed with mundane rather than creative associations, the ability to nonetheless perform creative production of associations is related to connectivity patterns between ECN regions and DMN regions (Beaty, Christensen, Benedek, Silvia, & Schacter, 2017). Nevertheless, lesion studies and neurostimulation studies found that decreased activity of the IFG, which results in reduced inhibitory control, seems to lead to increased creative production (Mayseless et al., 2014; Miller, Ponton, Benson, Cummings, & Mena, 1996, 2000; Seeley et al., 2008).

It is important to note that inhibition in the creative process pertains to the suppression of mundane ideas in favor of remote and original ones. Inhibition that constricts the scope of our semantic search to begin with would be detrimental for creativity. We propose that applying inhibitory control in a creativity-facilitating manner would require executive functions. As suggested elsewhere (Benedek & Fink, 2019), a slight reduction of cognitive control may support certain creative performances, by adjusting the balance of controlled and spontaneous processes toward preferable conditions for the given task (Benedek & Jauk, 2018; Chrysikou, Weber, & Thompson-Schill, 2014). In line with our assumption, direct investigation of the involvement of cognitive control during the creative process by neuroscientific means would shed more light on its debatable role, as the contribution of ECN might change across the different phases of the creative process.

Interestingly, highly creative participants showed increased coupling of DMN regions with the ECN during idea generation as well as other creative activities such as musical improvisation and poetry generation (Beaty et al., 2016a). This connectivity pattern points to a mechanism where controlled and spontaneous cognitive processes interact in creative cognition (Benedek & Fink, 2019; Zabelina & Andrews-Hanna, 2016). In this context, although the DMN may provide self-generated information via episodic retrieval, the ECN directs and monitors the integration of this information (Beaty, Seli, & Schacter, 2019). Similar to the interaction between these processes in creativity, it is reasonable to expect that cooperation between the DMN and ECN would benefit curiosity as well. Future studies should directly examine the role of cognitive control in curiosity and its interaction with the DMN.

Taken together, we suggest that cognitive control plays a key "gatekeeper" role both in curiosity and in creativity. Nevertheless, although some cognitive control is needed to attend novel stimuli around us as well as generate novel ideas, excessive control might hinder creativity (Runco & Basadur, 1993) and curiosity. The brain network dynamics, described next, determine the balance between spontaneous and controlled processes during curiosity and creativity, ultimately governing their maturation.

3.5 Brain network dynamics

It has previously been suggested that the interaction between the DMN and ECN reflects goal-directed, self-generated cognition, with the DMN involved in generative processes and the ECN in guiding, constraining, and modifying these processes to meet task goals (Beaty et al., 2016a; Ellamil, Dobson, Beeman, & Christoff, 2012; Mok, 2014). The interplay between the networks may reflect the cyclic motion between spontaneous and controlled processes during the curiosity/creativity process.

The SN is thought to be sensitive to bottom-up salience (Abraham, 2019) and to mediate interactions between internally and externally oriented attention (Menon & Uddin, 2010), and it is therefore possible that it is involved in tuning the balance between the DMN and ECN during the curiosity or creativity processes, depending on what is necessary in the current context (Abraham, 2019). In fact, the SN has been shown to moderate DMN–ECN interactions during creative idea production (Beaty et al., 2017; Goulden et al., 2014), and high functional connectivity between the three networks was found among highly creative individuals (Beaty et al., 2016a). Similarly, curiosity was found to be related to the functional connectivity of these three networks (Li et al., 2019).

In sum, creativity and curiosity are proposed to arise from the interplay between spontaneous and controlled processes, expressed by coupling of the DMN, ECN, and SN. Each of these networks is ascribed to a different and essential aspect of both. The DMN contributes to the integration of existing knowledge with novel information through flexible retrieval and search processes. The SN is thought to filter useful and novel candidate information and forward it to the ECN that evaluates and constrains this stream toward a specific goal by using flexible inhibition mechanisms. The dynamic interaction between these networks, together with subsequent memory and reward circuits, may postulate the underlying mechanism of curiosity and creativity. In the next section, we integrate the neurocognitive evidence from both fields into a unified model of novelty seeking.

4. The novelty-seeking model (NSM)

Based on the literature reviewed above, we propose a unified model that can encompass both curiosity and creativity, pointing to a similar involvement of generative and evaluative processes in both. This is in line with the dual-process models described above (e.g., Sowden et al., 2015). The proposed NSM is characterized by four distinct phases: *affinity*, *activation*, *evaluation*, and *commitment* (Fig. 1). These same four phases are proposed to be at the basis of creativity, curiosity, and all other novelty-seeking behaviors: First, attraction to a stimulus or a problem. Second, activation of the mental operations required to pursue it. Third, an iterative process of evaluating merit and relevance, and fourth, consolidation of what has crossed the threshold of interest in memory. We elaborate on each of these phases, after we describe our working terminology first.

Affinity: Any act of curiosity or creativity starts with affinity to a certain stimulation. *Stimulation* is the catalyst that triggers the process, be it an external stimulus or an internal idea. This affinity may be driven internally following a goal-directed search, such as an attempt to find some solution, or externally through a spontaneous encounter with something that attracts our attention and violates previous expectations. Affinity to stimulation depends on openness (SoM) and on the availability of mental resources. Because this phase relies on spontaneous processes and on search processes through semantic and autobiographical memory, among others, it is presumed to be mediated by the DMN (Beaty et al., 2016a; Benedek et al., 2018; Madore et al., 2019). We further suggest that affinity is expressed in curiosity as a unique scan path of the external environment (Krajbich, Lu,

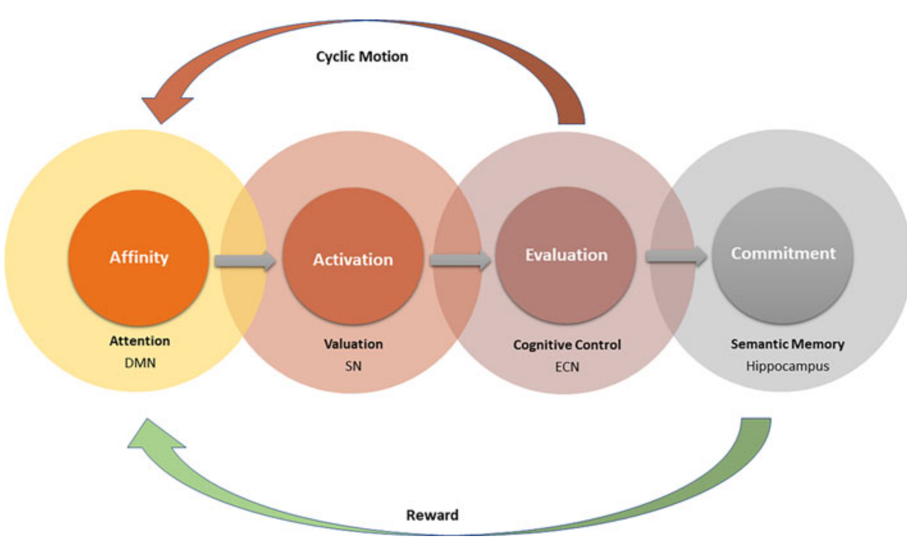

Figure 1. Four-phase model of the NSM. The process is initiated by an affinity toward novel internal or external stimulation and results in generation of novel combinations in a semantic network. The affinity phase relies on DMN activation as well as on attentional orientation. The candidate combinations potentially cross a relevance threshold in the activation phase, based on their saliency. This is followed by more deliberate and controlled processes in the evaluation phase, as each selected combination is being assessed. The process ends with commitment to memory, as a novel interlink is created in the semantic network, and then rewarded by the dopaminergic system.

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Camerer, & Rangel, 2012), and in creativity as a unique pattern of "random walks" (Abbott, Austerweil, & Griffiths, 2015, or shorter path length; Kenett et al., 2014) in the associative network. In curiosity, this is the stage by which the scope of attention directs the search toward the novel (Gottlieb, Cohanpour, Li, Singletary, & Zabeh, 2020). In creativity, this is the phase where the generation of novel stimulation is initiated, creating unique combinations in mind by integrating existing knowledge with novel internal or external information. The integration of external and internal stimuli is supported by inner–outer attentional fluctuations (Kucyi, Hove, Esterman, Matthew Hutchison, & Valera, 2017), which are suggested to take place in the DMN during the affinity phase.

Activation: The affinity phase ends with a set of prioritized representations, which initiates the spread of activation in the semantic network (the spreading-activation theory; Collins & Loftus, 1975). This spreading continues until an intersection between two concept nodes is found and a novel combination is generated in the network. *Combination* is the integration of existing knowledge with novel internal or external information. In creativity we combine remote associations in a novel manner, whereas in curiosity the combinations are made between prior knowledge and a novel stimulus to satisfy an information gap. In the activation phase, new combinations potentially cross a relevance threshold, depending on their saliency. Saliency is determined by various aspects such as novelty (Foley, Jangraw, Peck, & Gottlieb, 2014), personal relevance (e.g., goal, experience), SoM, perceptual saliency (e.g., brightness or color), or emotional saliency (e.g., a crying baby or a car accident). If the process is initiated voluntarily, the relevance threshold would reflect the level of interest, and if it is goal-directed, the threshold would reflect the goodness of fit between the stimulation and the goal.

The activation phase generates combinations, and those that cross the threshold are candidates for evaluation. We suggest that the activation phase is mediated by the salience network (SN), which determines the threshold and is responsible for the switching between the generative and evaluative processes (Abraham, 2019). The novelty of the stimulation is the key element according to which the combinations are evaluated and selected in later stages, together with its usefulness.

Evaluation: Each combination that has crossed the threshold is evaluated for its originality and usefulness. As opposed to the last two phases, evaluation is a systematic and deliberate process, using top-down information to examine the goodness of fit of the candidate combinations to the initial goal. There is a cyclic motion between the generation and the evaluation of combinations such that, although common or deviant combinations are rejected, novel and appropriate combinations receive further examination and elaboration. This phase is crucial for both curiosity and creativity as it enables us to narrow down the candidate combinations and to deeply explore them one by one. The evaluation phase relies on the valuation, monitoring, and selection of combinations, and these are commonly viewed as cognitive control processes (Benedek et al., 2018; Chrysikou, 2018; Ellamil et al., 2012; Kleinmintz et al., 2019). The involvement of cognitive control is essential for preventing overbursts of stimulation and to efficiently direct the available resources. Otherwise, no commitment through consolidation takes place.

Commitment: The process results, if the novel information is deemed worthy, in consolidation and categorization. Unlike previous models, we suggest that the NSM continues beyond the evaluation phase and ends with commitment to memory. The commitment phase is expressed by consolidating a novel combination in memory, that is, integration of novel stimuli into preexisting representations and thus the creation of new representations (Ranganath & Rainer, 2003; Schomaker & Meeter, 2015). This is more than mere consolidation; we commit to a combination we generated in previous stages, willing to invest our mental resources in further learning and elaboration. In curiosity, we commit to consolidating novel information in memory, whereas in creativity, we commit to the novel idea. The commitment phase ends with a call for action – elaboration and execution of an idea or further exploration of the novel stimulus. The process results in broadening of the associative network and scope of thinking and is mediated by the hippocampus. Hippocampal activity is reinforced by reward mechanisms that raise the chances for its persistence and reoccurrence (Duszkiewicz et al., 2019; Kafkas & Montaldi, 2018). The richer the memory structure is, the higher the efficacy of finding and establishing novel combinations (Gray et al., 2019). We, therefore, propose that the NSM originates and ends in memory.

5. The NSM within the context of dynamic changes in SoM

The novelty-seeking process contains inherent tensions, such as exploration–exploitation, focused–defocused attention, and originality–usefulness, which influence the form that curiosity and creativity will take. Here, we account for these trade-offs by linking the different types of curiosity and creativity with the dynamic and overarching SoM (Herz et al., 2020) that shapes them.

5.1 Different types of creativity and curiosity and their attribution to SoM

It is increasingly acknowledged that curiosity is comprised of two types: feelings of *general interest* (also known as diversive curiosity), which motivate diverse exploration, and feelings of *deprivation* (also known as specific curiosity), which promote specific exploration and aim to solve specific problems (Litman, 2008). Although interest is motivated by positive feelings and by the opportunity to learn something new, deprivation, on the other hand, can be seen as a need that drives us to reduce the feeling of uncertainty by acquiring missing information (Litman, 2008). Following Litman's discrimination, it is important to note that on the continuum of interest–deprivation, deprivation may arise out of a need to fill the gap and to reduce uncertainty, whereas interest is less related to anxiety and more to creativity. As proposed above, we hypothesize that in an exploratory SoM, curiosity would expand the scope of our stream of thoughts and enable creativity to arise in an uncertain environment. On the other hand, in an exploitatory SoM, the same information might be perceived as overwhelming and invoke anxiety, so curiosity will take the form of deprivation, promoting narrow and specific exploration, thus leaving no room for new ideas to arise. This hypothesis is partially supported by a recent study (Lauriola et al., 2015) that showed a positive correlation between interest, fun seeking, positive expectancies, and risk taking, which orients participants toward exploration, and vice versa. Exploitation was positively correlated with thoughtful evaluation and concern over negative outcomes and potential risks, orienting participants toward caution regarding knowledge search.

Creativity, as well, involves two modes of thinking: *convergent* and *divergent*. Convergent thinking (CT) refers to a single solution to a given problem, as opposed to divergent thinking (DT), which refers to the extrapolation of many possible responses to an initial stimulus (Guilford, 1967). DT requires combining information in novel ways, linking remote associates or transforming information into unexpected forms, CT involves manipulation of existing knowledge by applying more logical search, recognition, and decision-making techniques to derive the best solution (Cropley, 2006). These two modes of thinking are necessary to produce novel ideas and are shifted during the creative process, as described above (Guilford, 1956).

We suggest that the subtypes of curiosity and creativity are parallel: *Open-ended novelty-seeking* curiosity is similar to DT, as multiple options are acceptable. *Goal-directed novelty-seeking* curiosity, on the other hand, includes the specific/deprivation type, which is similar to CT when the focus is on a single option in a predetermined task. Some support for this notion comes from a recent study that measured these subtypes of curiosity and creativity by using lab-based tasks (Koutstaal, Kedrick, & Gonzalez-Brito, 2022). The authors found a positive correlation between the novelty of the questions that participants generated during a curiosity Q&A task and the originality of their responses on a DT task. Notably, performance in both tasks was positively correlated with the trait-based interest type but not with the deprivation type. On the other hand, the extent to which participants sought out missing information regarding the presented stimuli in the curiosity task (referred to by the authors as "gap-related information foraging") positively correlated with CT tasks. In line with that, in a recent meta-analysis, that examined the relationship between the two (Schutte & Malouff, 2019), the authors suggested that the exploration dimension of curiosity may be more relevant for creativity than the deprivation sensitivity dimension.

Another important distinction that should be made is between the two components of creative ideas, that is, originality and usefulness (Amabile, 1993; Stein, 1953; Sternberg & Lubart, 1999). Although both are essential for creativity (otherwise, ideas would be either non-original or inappropriate), they require different abilities. *Originality* refers to breaking existing frames, whereas *usefulness* refers to the practical qualities, acceptance by other people, and adherence to cultural norms (Morris & Leung, 2010). It is noteworthy that creative people have been found to excel in both dimensions of creativity (Miron-Spektor & Erez, 2017) and that originality and usefulness are also interdependent, reinforcing each other during the creative process (Lewis, 2000). According to Miron-Spektor and Erez (2017), "Novel insights can help improve product usefulness, and considering usefulness issues can inspire novel ideas" (p. 4). Thus, to produce a creative solution, problem solvers must also find a way to manage usefulness after establishing novelty (Amabile, 1996; Berg, 1991; Litchfield, 2008).

We suggest that the close relationship between these different types of curiosity and creativity are best captured by the SoM framework (Fig. 2). Although exploration results in diversity, exploitation results in specificity. Therefore, DT, diversive curiosity, and originality orientation would be related to exploration, whereas CT, specific curiosity, and usefulness would be associated with exploitation. It is important to note that one is rarely at either extreme of this SoM continuum, but rather dynamically alters between the different modes based on situational demands.

5.2 Flexible control dynamics

Much like the trade-off between exploration–exploitation, adaptive levels of control might be indicative of cognitive flexibility and benefit novelty seeking. Therefore, the ability to flexibly switch between inhibition/disinhibition and exploration/exploitation might lead to an optimal novelty-seeking performance, that is, generating/consolidating novel and useful knowledge.

We suggest that cognitive control tunes the flow of stimulation by screening which input will enter, and what ideas will arise. In this framework, disinhibition results in an overflow of stimulation that may not be translated into an output that is a product of creativity or curiosity, whereas hyper-inhibition may lead to a stand-still when we stick to existing knowledge and a premature closure of ideas that could otherwise be further developed (Runco & Basadur, 1993). The interaction between these two factors results in different types of curiosity and creativity. These manifestations could be explained using the matrix portrayed in Figure 3. The position on this two-axis matrix determines the quality and quantity of the NSM. The cross-points between the axes determine the expression the NSM will take. Once activated, the degree to which each type of curiosity/creativity is experienced and behaviorally expressed varies according to individual differences and task constraints. At the extremes, hyper-inhibition × exploitation would result in a stand-still state when we stick with our previous knowledge, whereas disinhibition × exploration results in an overflow of information and bizarre ideas.

When we are somewhere in the middle along this continuum, the NSM is expressed in various ways. Exploration × inhibitory control will result in a CT mode, which requires the elimination of incorrect solutions, yet it also finds the right creative solution. Exploitation × inhibitory control will result in usefulness: Generating practical solutions and looking for specific information. Exploitation × disinhibition will result in the elaboration of existing ideas, and exploration × disinhibition might result in non-original ideas. The balanced condition will result in DT and diversive curiosity (interest). Using the matrix, one can better understand why it is not a matter of either–or, but rather a dynamic interplay between "opposing" forces that are altered throughout the process and determine the different manifestations of the NSM. This is based on the relative weight and balance between the forces and is influenced by the context demands and

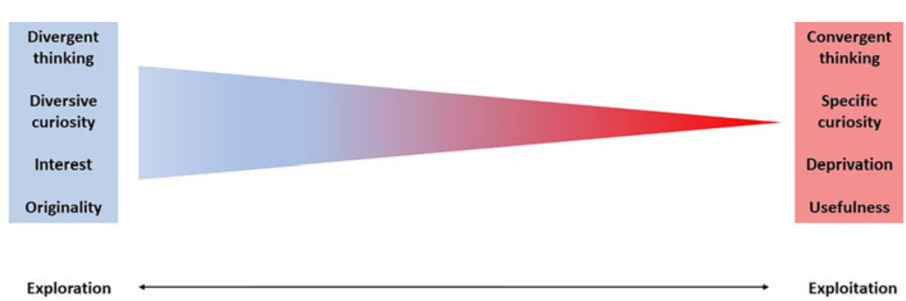

Figure 2. Effects of SoM on the NSM. Illustration of the continuum of SoM ranging from broad to narrow in relation to the NSM. At the left endpoint broad SoM consists of an exploratory disposition that results in diversity; thus, it is associated with divergent thinking, diverse curiosity, and an originality orientation. At the right endpoint, narrow SoM consists of an exploitatory disposition, resulting in specificity. Therefore, convergent thinking, specific curiosity, and a usefulness orientation are associated with exploitation.

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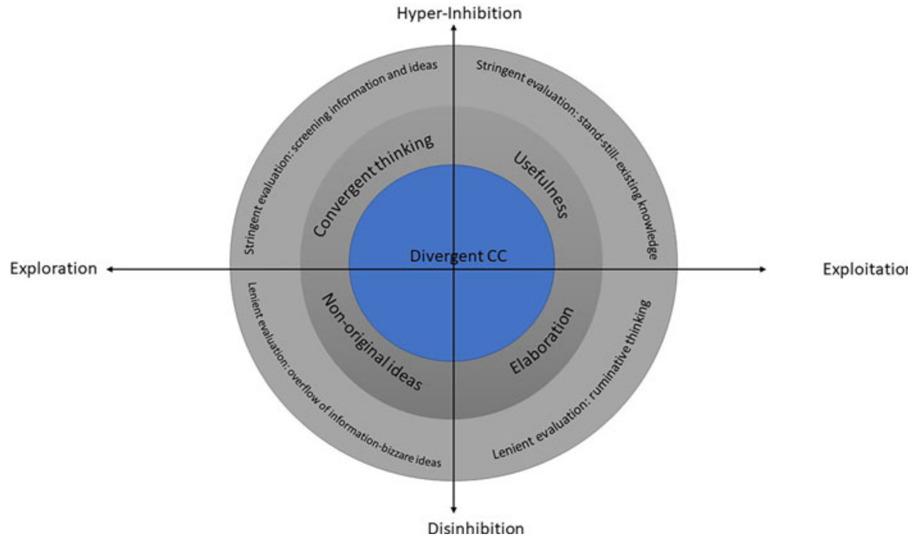

Figure 3. Different types of curiosity and creativity, as manifested by the SoM × inhibitory control matrix. The interaction between SoM and inhibitory control results in different types of curiosity and creativity. The position on this two-axis matrix determines the quality and quantity of the NSM. The central circle represents a balanced interaction between the two factors, and results in an ideal expression of divergence as one moves toward the endpoints of the continuum.

available resources. If so, flexibility is key to enhance both curiosity and creativity.

5.3 Clinical perspective

Our framework provides the basis for characterizing various psychopathologies in relation to the NSM. Although much has already been written about the relationship between creativity and psychopathology (e.g., Abraham, 2014; Carson, 2011; Herz et al., 2020; Jung, Grazioplene, Caprihan, Chavez, & Haier, 2010; Post, 1994; Simonton, 2003), research into curiosity and psychopathology is still lacking. The suggested matrix, with the SoM × inhibition axes, has potential clinical implications. At one extreme of the matrix, schizophrenic individuals are characterized by hyper-exploration × disinhibition, which results in delirium and bizarre ideas, rather than in original ones. Considering that such individuals also suffer from a decreased level of semantic processing (Pomarol-Clotet, Oh, Laws, & McKenna, 2008) and impaired episodic memory (Goldberg, Keefe, Goldman, Robinson, & Harvey, 2010), both of which are crucial for associative thinking, could further explain why the NSM takes an extreme and pathological manifestation in such cases.

At the other extreme, and far from the myth of the "tormented yet creative artist," depression can be characterized by exploitation × hyper-inhibition, resulting in a narrowed scope of associative thinking (perseveration of an extremely narrow SoM; Herz et al., 2020) that might be expressed as pathological ruminations (repetitive thought patters, e.g., Nolen-Hoeksema, 2000). In this case, increased self-referential processing (i.e., the tendency to experience stimuli as strongly related to one's own person; Northoff et al., 2006; Wright & Beck, 1983), together with a high probability of reliance upon top-down processing (Herz et al., 2020), leaves no resources for exploring the environment, and results in a lower motivation for novelty seeking. In line with this suggested conceptualization, bipolar affective disorder is characterized by alterations between exploration–exploitation and inhibition–disinhibition. Therefore, the critical point for the NSM to occur, in that instance, would be in the transition between the depressive and manic episodes. Indeed, bipolar disorder was suggested to interweave creative accomplishments (see Johnson et al., 2012, for a review), and higher rates of the disorder have been found among famous artists, musicians, and writers (Goodwin & Jamison, 2007; Ludwig, 1992; Rothenberg, 2001).

Lastly, it is important to note that although curiosity and creativity are part of the same process, the emphasis can be switched from one entity to the other (when you are creative, you are x% curious and vice versa). Therefore, people can be highly curious, but not necessarily creative. An example of such a case is Asperger's syndrome, in which individuals have high-specific curiosity to such an extent that they can memorize a specific field of knowledge by heart, but they lack the flexibility to be creative. Considering that high-functioning autistic individuals show a deficit in tasks that require cognitive switching, whereas their cognitive inhibition is intact (Kleinhans, Akshoomoff, & Delis, 2005) supports this notion and, according to our matrix, implies that Asperger's individuals can be characterized by hyper-inhibition × exploitation. Therefore, the NSM depends on the ability to flexibly alternate between different levels of cognitive mechanisms. Although these cases might challenge our framework, they set the stage for future in-depth studies that should test the inter-relations between the dimensions of curiosity and creativity in various conditions and populations. Future studies should design tasks that directly measure the unified process rather than each construct separately.

6. Implications and future directions

In this article, we postulated that a unified process of novelty seeking may be shared in underlying both creativity and curiosity. We provided a modified model (NSM), which expands previous dual-process models, and demonstrated how curiosity and creativity similarly evolve through each of the four stages of the model. We suggest that the NSM begins with an affinity toward the novel that is manifested by a specific pattern of neural firing, initiated by the novelty of response. Using this framework, one can imagine how attentional fluctuations can tilt the system toward a specific stimulus or idea at a random moment in time. In this manner, an attentional spotlight is directed to what we perceive as novel in curiosity, whereas in creativity, similar attentional processes are applied in order to generate novel concepts along the network of stored representations. Diverse thinking enlarges the

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spotlight, and more information is obtained. By expanding our knowledge, our memory becomes more interconnected, and we are more likely to reach remote associations. It is a loop of feeding and generating: The more combinations cross the novelty threshold, the more interconnected our memory becomes, which will eventually raise the chances that the NSM will be initiated once again.

This is a cyclical process in which one walks through all the stages to be creative or curious. Iterations of the process may result in greater affinity via expansion of memory, and this iterative process potentially explains the reinforcing nature of both curiosity and creativity. That said, it should be noted that although we propose shared mechanisms for curiosity and creativity, and although evidence points to the possibility that curiosity may set the stage for creative thinking, empirical evidence to support a causal relationship between the two is still very scarce (Gross, Zedelius, & Schooler, 2020). It may be that curiosity is an impetus for problem identification and information gathering, upon which further processes leading to creativity then build. On the other hand, it might be that creative behavior positively engages individuals so that they want to know more, resulting in greater curiosity (Schutte & Malouff, 2020). To date, very few studies have experimentally manipulated curiosity to look for causal effects. The aforementioned studies are correlational and rely on self-reported trait measures of curiosity. Indeed, one issue that currently limits curiosity research is the lack of behavioral measures that assess curiosity as a psychological state (Gross et al., 2020). This is especially prominent in comparison to creativity research, where a vast selection of tasks may result in inconsistent results. Future studies should design such behavioral tasks and induce, for example, a curious state prior to creative thinking tasks, in order to shed light on the causal relationship between the two.

Following the SoM framework (Herz et al., 2020), we further suggested that although the flexible alterations between exploratory and exploitatory SoMs are essential for both creativity and curiosity, they do not have equal utility. Both behaviors stem mainly from exploratory orientation and its interlinked dimensions, such as defocused attention and bottom-up processing. Exploitatory SoM on the other hand, associated with top-down control, balances and directs the process, but novelty seeking that drives curiosity and creativity is primarily encapsulated in an exploratory SoM.

The theoretical framework suggested here, according to which curiosity and creativity are two manifestations of a unified process, has several implications. Acknowledging the underlying mechanisms of the NSM, and experimentally manipulating them, may help to enhance curiosity and creativity by need. This can be tested experimentally in behavioral methods, such as cognitive stimulation, that would influence the processing resources needed to unleash novelty-seeking behavior. Furthermore, targeting the neural mechanisms underlying the NSM by means of direct neural stimulation could potentially enhance novelty-seeking behavior as well. This notion was already tested in creativity using transcranial direct current stimulation (tDCS; see Lucchiari, Sala, & Vanutelli, 2018, for a review), transcranial magnetic stimulation (TMS; e.g., Flaherty, 2005), and neurofeedback (Gruzelier, 2014), but to date, such efforts in the field of curiosity are still to come.

Our efforts to link curiosity and creativity are wrought of some limitations. First and foremost, to delineate our discussion within existing research, here we referred to both curiosity and creativity in a narrow context of which they are controllably operationalized and measured in the lab. From the same reasons, here we mainly embraced a neurocognitive perspective. Although we are aware that both are multifaceted and entail much more than the context described in the current article (educational and developmental perspectives, artistic or Big C creativity, personality traits, to mention a few) we hope that the theoretical framework proposed here may apply to curiosity and creativity "in the wild." As more detailed discussion regarding other facets of curiosity and creativity are beyond the scope of this article, we encourage future research to investigate their relationship in different contexts and perspectives.

Second, the shared cognitive faculties and brain networks involved in creativity and curiosity included in the NSM are involved in many aspects of cognition. Similar to other complex constructs, although these mechanisms are not solely underlying curiosity and creativity, we aimed to conceptually establish a link between the two by showing how those faculties change in tandem. Once the link between curiosity and creativity has been created, we hope that it will serve as a foundation for further theorizing about the nature of their unified process.

7. Concluding remarks

It may be common knowledge that curious people are more creative, but surprisingly, no systematic investigation has been conducted so far to explain why and how this may be true. Here, we reviewed cognitive and neural mechanisms that might explain the intuitive link between curiosity and creativity and, for the first time, provide a systematic explanation for their relationship. We propose that both are manifestations of a unified process that underlies novelty seeking, as illustrated by a novelty-seeking model. We claim that both have a reinforcing nature, the more curious and creative you are, the higher your sensitivity to novel stimuli would be. Lastly, we demonstrated how our state of mind determines which form curiosity and creativity will take. We believe that integrating curiosity and creativity under one perspective can, in turn, facilitate greater intrafield understanding of both processes.

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Open Peer Commentary

Novelty seeking might underlie curiosity and the novelty dimension of creativity, but not the usefulness dimension

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Abstract

We question the perspective that curiosity and creativity stem from a shared novelty-seeking process. We emphasize that creativity has two distinct dimensions: Novelty and usefulness, each involving separate cognitive processes. These dimensions may not necessarily mutually reinforce each other. We contend that a more comprehensive model that encompasses the full scope of the creativity construct is needed.

In their article, Ivancovsky et al. posit that curiosity and creativity are "manifestations of the same novelty-seeking process" (target article, short abstract). Although their proposed novelty-seeking model is thought-provoking, we advocate for a more nuanced perspective that acknowledges the significant differences between the two core dimensions of creativity – novelty and usefulness. We argue that their proposed model may be valid for novelty but its applicability to usefulness is uncertain.

Central to the author team's argument is a shared cognitive and motivational basis for curiosity and creativity. However, prior research has documented substantial differences in terms of how identical cognitive and motivational constructs affect novelty and usefulness (e.g., Acar, 2018; Baas, De Dreu, & Nijstad, 2008; Mehta & Zhu, 2016; Miron-Spektor & Beenen, 2015). For example, Miron-Spektor and Beenen (2015) found that learning achievement goals, likely common among many curious individuals (as discussed in Ivancovsky et al.), drive novelty, through increased cognitive flexibility, but not usefulness. In contrast, performance achievement goals drive usefulness through cognitive closure, but not novelty.

Ivancovsky et al. seek to resolve this issue by distinguishing between two forms of curiosity – diversive and specific – and connecting (i) novelty to diversive curiosity, exploration, and divergent thinking, and (ii) usefulness to specific curiosity, exploitation, and convergent thinking. Although potentially promising, this perspective raises several issues. First, the empirical foundation for these proposed connections is not sufficiently established. Second, the theoretical rationale behind connecting specific curiosity to other constructs remains unclear. For instance, it is unclear how specific curiosity aligns with convergent thinking, which requires accuracy, logic, and risk aversion (Cropley, 2006) – qualities that typically contradict novelty seeking. It is also unclear why specific curiosity should be more closely connected to exploitation rather than exploration. Third, because creativity entails both novelty and usefulness, it is implied that both diversive and specific curiosity must coexist in creative pursuits, raising questions about whether this can consistently be the case. These issues do not directly refute the authors' propositions but highlight the need for a more precise theoretical development and stronger empirical evidence.

Furthermore, we question whether the authors' portrayal of novelty and usefulness as mutually reinforcing represents the entire body of creativity literature. Notably, Miron-Spektor and Erez (2017), whom the authors cite to support their perspective, later state that "novelty and usefulness also derive from distinct, incongruent psychological processes" (p. 7). In fact, a considerable body of research suggests that novelty and usefulness are inherently incompatible and may even be negatively correlated (e.g., Diedrich, Benedek, Jauk, & Neubauer, 2015; McCarthy, Chen, & McNamee, 2018; Paletz & Peng, 2008; Runco & Charles, 1993; Steele, Hardy, Day, Watts, & Mumford, 2021; Sullivan & Ford, 2010). For example, Diedrich et al. (2015) found strong and significant negative correlations between novelty and usefulness across two different tasks ($rs = -0.55$ and -0.48; $ps < 0.01$). It is therefore not surprising that individuals frequently struggle to reconcile these two dimensions, sometimes even perceiving them as contradictory (e.g., Rietzschel, Nijstad, & Stroebe, 2010; Zhou, Wang, Bavato, Tasselli, & Wu, 2019) – although individuals often appreciate useful ideas, they tend to be negatively biased against novel ones (e.g., Mueller, Melwani, & Goncalo, 2012). A major strand of creativity research neither does perceive the connection between novelty and usefulness as "paradoxical," nor does it assert that they are mutually reinforcing; instead, this body of research regards these two dimensions as independent contributors to creativity (see Harvey & Berry, 2023, for a review of different perspectives on how usefulness and novelty are related).

Importantly, there are reasons to expect that novelty seeking might be unrelated to, or even detrimental to, usefulness. Curious individuals might have a higher motivation to maximize the creation of novel experiences, rather than focusing on what is appropriate or valuable in a given context. In essence, curiosity might encourage creating novel solutions that might come at the expense of producing useful content. This perspective aligns with motivational accounts of creativity. Amabile (1996), for example, suggests that curiosity and interest, which are components of intrinsic motivation, are crucial in the initial creative phase but become less dominant in later stages, where an idea's usefulness often determines its creative value. Moreover, after reviewing a diverse set of empirical studies, Grant and Berry (2011) concluded that intrinsic motivation drives the generation of novel ideas but not necessarily useful ones. They also referred to an early study by Barron (1963), which demonstrated that many intrinsically motivated architects struggled to produce creative outputs because they prioritized the novelty of their designs over their practicality. This argument is also consistent with empirical research showing that individuals with a strong motivation to acquire new knowledge generate less useful solutions to innovation problems (Acar, 2019).

In conclusion, although the authors' novelty-seeking model presents an interesting perspective on the relationship between curiosity and creativity, it may not sufficiently account for the complexity of the creativity construct. This line of argumentation aligns with the views of other creativity scholars who, recognizing this complexity, have suggested that the generation of creative outcomes requires multiple processes and components (e.g., Amabile, 1996; Baas et al., 2008; Batey & Furnham, 2006; Gruys, Munshi, & Dewett, 2011). We believe that the applicability of the proposed novelty-seeking model may be more suited to domains where usefulness is less of a priority, such as artistic creativity. We also believe that a more nuanced model that recognizes the distinction between novelty and usefulness is essential for a more comprehensive understanding of the creative processes in various domains.

Competing interest. None.

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The creativity of architects

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Abstract

TA builds on the state of mind (SoM) framework to offer the novelty-seeking model (NSM). The model relates curiosity to creativity but this commentary focuses on creativity: (i) It assesses the SoM + NSM model of creativity-in-the-lab, showing that the focus on semantic networks is inadequate. (ii) It discusses architectural design to sketch ideas for a theory of "big C" creativity.

Assessing the SoM + NSM model

Established notions of exploitation and exploration gain no extra strength from the state of mind (SoM) framework. It seems to have no predictive power. TA Figure 2 offers a continuum that lumps diverse dichotomies including Open-Ended↔Goal-Directed, Interest↔Deprivation, and Originality↔Usefulness as if they were respective components of two contrasting states of mind, rather than assessing whether each pair or component involves different systems whose contributions must be distinguished. The continuum does not help us organize analysis of the contributions of the default mode network (DMN), salience network (SN), and executive control network (ECN) posited for novelty-seeking model (NSM). A useful exercise would be to carefully define the terms of Figure 2 and analyze their relation to interactions within DMN-SN-ECN.

TA§6 note that "The … brain networks … included in the NSM are involved in many aspects of cognition [and] not solely underlying … creativity." My concern is that, by ignoring data from other aspects of cognition, TA leaves DMN, SN, and ECN and HC as unanalyzed "lumps," depriving us of the opportunity to assess how the way their constituent circuits serve diverse roles in quotidian behavior may illuminate their roles in creativity.

TA finds it "reasonable to assume that intrinsic and extrinsic motivation could synergistically benefit creativity … Intrinsic motivation may be essential for the novelty component, just like exploratory SoM, while extrinsic motivation can help to ensure perseverance and elaboration, similar to exploitatory SoM." But it remains unclear whether the SoM framework adds anything here.

NSM posits four phases: *Affinity* generates novel combinations in a semantic network, in A*ctivation* salient combinations potentially cross a relevance threshold, *Evaluation* further assesses combinations, and in *Commitment* the hippocampus is engaged as a novel interlink is created in the semantic network. However, adding links to a semantic network seems a poor framework for a theory of creativity. Unfortunately, TA is almost devoid of examples. One of the (two?) exceptions is "the Remote Associates Test, which requires participants to find a common element among three seemingly unrelated concepts (e.g., *mines*, *lick*, *sprinkle*) and to generate a fourth item related to each item in the trio (e.g., *salt*)." Here, then, the nodes of the semantic network seem to be words with their meaning-items, with a link between two nodes if they share a meaning-item. "Creativity" in this case involves finding words associated with more than one of the three targets (Affinity) until one is found that is associated with all three (Evaluation). The result is then that word, but no new link is added to the semantic network. Rather, a working memory gathers and evaluates existing links, and there is no Consolidation once the test has been completed.

Linking two ideas may be a crucial part of creativity (recall Koestler's bisociation – Koestler, 1964; Miller, 1964) but, in general, this only one step in creating new and more complex structures. Indeed, tests of in-the-lab-creativity through assessing and making drawings involve novel "constructions" rather than new links in a semantic network, and there are many relevant studies of hippocampus (Moscovitch, Cabeza, Winocur, & Nadel, 2016; Schacter & Addis, 2020; Summerfield, Hassabis, & Maguire, 2010).

Designing buildings

Recent work (Arbib, 2020, 2021) analyzes how architects design buildings, constructing new patterns in memory (in diverse brains and the external representations) that cumulatively yield a plan for a new building. The architect does not manipulate an extant semantic network but instead creates rich "mental constructions" that can guide the physical construction of buildings – devising spaces and shaping and relating forms to serve stipulated functions, be aesthetically pleasing, conform with the site, and be built with available funds.

In the VISIONS model of interpreting visual scenes (Hanson & Riseman, 1978), perceptual schemas compete and cooperate to interpret regions of the scene and relations between them. Perception "clamps" *retinal input* to drive schema activation and interpretation. "Bottom-up" processing integrates input data as one basis for activating schema instances, but once some schema instances are activated, perhaps by outside considerations (Yarbus, 1967), "top-down" processes come into play. Perception is here a form of mental construction.

The experience of a building is multisensory, and design may involve constructing physical models to offer a genuine feel of spatial relations, but much of design involves drawing. Visual imagination "inverts" vision, "clamping" *interpretation* and some constraints on schemas to drive top-down activation of schema instances and feature maps. But the resultant drawings can then stimulate and anchor further creativity.

Turning to movement and navigation in space: In a World Graph, a node corresponds to a significant place, and each edge represents a direct path from one such place to another (Arbib & Bonaiuto, 2012; Lieblich & Arbib, 1982, in BBS). A WG may link to a *locometric map* which charts patterns of locomotion in physical space.

Designers exploit their own diverse forms of long-term memory – episodic, procedural, and semantic – to design spaces that will structure the experience of the building's users as they develop behaviors that, at least in part, emerge as variations on the scripts (patterns of behavior that can be adapted to varied circumstances) the architect imagined. Our modeling (Arbib, 2020, 2021) extends navigation to controlling transitions between affordances (opportunities for action) in supporting the constraints of scripts. The architect must transform each script into design ideas for a WG linking places that need to be included in a building to satisfy the script. But a design that specifies separate places for each script may be both uneconomical and inconvenient. An assessment is thus required of which places to merge, unifying WGs in the process. Only the registration of the WG with a locometric map makes the factoring of effort into executability possible.

There are vast realms of empirical data left to be explored and discovered and much further modeling to be done – modeling that goes far beyond semantic networks to enrich future contributions of the neuroscience of creativity to our understanding of the experience and design of architecture.

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Distinct neurocognitive pathways underlying creativity: An integrative approach

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Abstract

By examining the shared neuro-cognitive correlates of curiosity and creativity, we better understand the brain basis of creativity. However, by only examining shared components, important neuro-cognitive correlates are overlooked. Here, we argue that any comprehensive brain model of creativity should consider multiple cognitive processes and, alongside the interplay between brain networks, also the neurochemistry and neural oscillations that underly creativity.

By integrating research on the shared cognitive and neural correlates of curiosity and creativity, Ivancovsky, Baror, and Bar offer insight into the brain origins of creativity. Yet, by only examining their shared components, important cognitive processes and brain correlates of creativity are overlooked. We argue here that true understanding of the brain basis of creativity should, alongside the interplay among brain networks, include multiple cognitive pathways to creativity and their underlying neurochemistry and neural oscillations.

Regarding cognitive pathways to creativity, there is robust evidence that creativity is a function of multiple independent cognitive processes (e.g., Benedek & Fink, 2019; Mumford, Reiter-Palmon, & Redmond, 1994; Nijstad, De Dreu, Rietzschel, & Baas, 2010; Zhang, Sjoerd, & Hommel, 2020). For example, original ideas emerge when someone flexibly explores and combines remote material from memory or the environment. This flexibility pathway to creative ideation involves using and switching between broad and inclusive cognitive categories, divergent thinking, and combining remote (rather than close) associations. However, equally original ideas can emerge when someone systematically explores a semantic category in depth. This persistence pathway to creative ideation results in original ideas only after more readily available ideas within a semantic category have been examined and discarded (Nijstad et al., 2010; Ward, 1994). The persistence pathway involves generating a large number of ideas within few semantic categories, and an incremental and systematic idea search, where original ideas emerge later in the process (De Dreu, Baas, & Nijstad, 2008).

That equally creative ideas can result from distinct cognitive processes matters because many individual differences and psychological states can be linked to creativity through one of these processes. Indeed, the flexibility pathway associates with curiosity, openness to experience, and novelty seeking (Gocłowska, Ritter, Elliot, & Baas, 2019; Ivancovsky et al.), but also with a happy mood (De Dreu et al., 2008), a focus on obtaining desirable outcomes (Baas, De Dreu, & Nijstad, 2011), and (trait) mindfulness (Baas, Nevicka, & Ten Velden, 2014; Lebuda, Zabelina, & Karwowski, 2016). Persistence, in contrast, links to working memory capacity (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012), negative affective states like anxiety and anger (De Dreu et al., 2008) and threatening circumstances (Baas et al., 2011, 2019; Perchtold-Stefan, Papousek, Rominger, & Fink, 2022). This explains why curiosity for intense negative information (morbid curiosity) does not necessarily result in a large variety of creative ideas, but may specifically trigger novel ideas aimed at damaging others (Perchtold-Stefan et al., 2022). More generally, these findings question how the Novelty-seeking Model captures these different cognitive processes and morbid curiosity effects.

Like the Novelty-seeking Model, flexibility and persistence involve a complex interplay between brain networks, including the default mode network and the dopamine-innervated fronto-striatal circuitry (Beversdorf, 2019; Boot, Baas, van Gaal, Cools, & De Dreu, 2017a; De Dreu et al., 2014, 2024; Zhang et al., 2020). For instance, cognitive flexibility involves the default mode network and neural activity in the striatum, a brain region involved in reward processing, updating of goal representations, and shifting task strategies (Boot et al., 2017a; Gvirts et al., 2017; Kehagia, Murray, & Robbins, 2010). Cognitive persistence relies more on neural activity in the (dorsolateral and orbitofrontal) prefrontal cortex (Kane & Engle, 2002). This explains how differential neurochemical processes, including surges in dopamine, oxytocin, and norepinephrine may differentially affect cognitive flexibility and persistence, ultimately feeding into creative thinking and doing (Beversdorf, 2019; De Dreu, Nijstad, & Baas, 2024). These insights further provide a basis to understand the link between psychopathologies and creativity (Baas, Boot, Nijstad, & De Dreu, 2016), and to conceptualize how flexibility and persistence can be balanced in the brain to avoid distractibility and bizarre ideas on the one hand (too much flexibility) or rigidity on the other (too much persistence) (Boot et al., 2017a).

One promising avenue for understanding the brain basis of curiosity and creativity that is ignored in the Novelty-seeking Model is the role of neural oscillations that are captured by EEG. Compared to MRI, EEG delivers superior time-resolution to capture the fast neural events involved in creativity (e.g., insight; Kounios & Beeman, 2009). Numerous EEG studies have identified local and global alpha power as a robust correlate of creativity (Fink & Benedek, 2014; Perchtold-Stefan et al., 2022, 2023). Task-related changes in alpha power distinguish less and more creatively demanding tasks, less and more creative people, lower and higher creative performance, and less and more creative ideas within-person (Fink & Benedek, 2014; Stevens & Zabelina, 2019). Notably, creativity-related alpha increases reveal topographically distinct insights into the complexity of cognitive processes in creative ideation: Increases at frontal cortical sites have been linked to executive functioning, increases at (right) temporal sites to the connection of remote associations, and increases at (right) parietal sites to internally directed attention (Perchtold-Stefan, Rominger, Papousek, & Fink, 2023). These oscillatory alpha patterns of creativity are remarkably similar for different life domains, including playing soccer, creative emotion regulation, and musical improvisation (Fink & Benedek, 2019; Perchtold-Stefan et al., 2022). Also, neurostimulation of alpha power has yielded selective improvements in creativity, and trainings to boost creativity have simultaneously increased alpha power in the brain (Perchtold-Stefan et al., 2022; Stevens & Zabelina, 2019). Other EEG frequency bands were shown to modulate creativity as well (for delta, see Boot, Baas, Mulhfeld, De Dreu, & Van Gaal, 2017b), and interestingly, studies have also documented links of alpha/beta oscillations with curiosity and novelty seeking (Alicart, Cucurell, & Marco-Pallares, 2020; Käckenmester, Kroencke, & Wacker, 2018). In sum, including neural oscillations has tremendous potential for illuminating the complex and transient processes of creativity to reveal insights into the (neural) link between creativity and curiosity.

To conclude, understanding the shared neural basis for curiosity and creativity requires a good grasp of the neurobiology of each. Here, we focused on emerging work on the neurocognitive basis of creativity. We showed that multiple distinct neurobiological systems and cognitive processes operate that support creative outcomes, some of which may be at odds with curiosity. The same may be true for (morbid) curiosity. Regardless, it has become apparent that only a combination of (insights from) different neuroscience methods will ultimately reveal how creativity works in the brain.

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Prediction error minimization as a common computational principle for curiosity and creativity

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Abstract

We propose expanding the authors' shared novelty-seeking basis for creativity and curiosity by emphasizing an underlying computational principle: Minimizing prediction errors (mismatch between predictions and incoming data). Curiosity is tied to the anticipation of minimizing prediction errors through future, novel information, whereas creative AHA moments are connected to the actual minimization of prediction errors through current, novel information.

The authors Ivancovsky, Baror & Bar aim to reconcile the phenomena of *creativity* and *curiosity* via a shared novelty-seeking basis. For this, they describe common cognitive key features such as memory, cognitive control, attention and reward including empirical evidence from network neuroscience. We agree with their efforts to reconcile those concepts under one explanatory framework. However, we argue that it can be further expanded by linking the novelty-seeking basis to the process of *prediction error minimization* – a common underlying computational principle both central to predictive coding (Clark, 2013) and reinforcement learning theories (Glimcher, 2011). This principle connects both phenomena as has been argued before (Friston et al., 2017; Van de Cruys et al., 2021).

According to predictive coding theories, our sensory and cognitive systems have a fundamental aim: Constructing reliable representations of the world to enable adaptive behaviour. To this end, the brain engages in a process of generating predictions about its own perceptual experiences, actions and cognitive processes serving as models of those experiences and processes (Den Ouden, Kok, & De Lange, 2012). These predictions are subsequently compared with the corresponding incoming sensory, motor or cognitive input, resulting in the computation of a prediction error (Den Ouden et al., 2012). The bigger the mismatch between input and predictions, the bigger the resulting error, prompting an update to those predictive models which ultimately forms the basis for learning (Friston & Kiebel, 2009). Prediction errors can be unsigned, representing the magnitude of the *surprise* related to a perception or cognitive outcome. Prediction errors can also be signed, indicating the valence of the outcome (whether it is better or worse than expected) often related to *reward* (Den Ouden et al., 2012). Importantly, the concept of prediction errors are inherently related to novelty because minimizing prediction errors by updating one's models entails constantly seeking out unexpected, novel information. This process again leads to more prediction errors generating a continuous cycle of learning and adaptation (Schwartenbeck, FitzGerald, Mathys, Dolan, & Friston, 2015).

From this perspective, curiosity and creative problem solving are two phenomena that relate to different aspects within this same continuous *prediction error minimization* process. Consistent with this view, the phenomenology and neurobiology of curiosity (Gruber, Gelman, & Ranganath, 2014; Gruber & Ranganath, 2019) and creative problem solving (Becker, Wang, & Cabeza, 2023; Dubey, Ho, Mehta, & Griffiths, 2021; Friston et al., 2017; Savinova & Korovkin, 2022), have both been explained via different kinds of signed and unsigned prediction error signals. In the following, we argue that curiosity reflects *expected information gain* while creative problem solving or at least its end result – the AHA experience – represents *absolute information gain* (Van de Cruys et al., 2021). Information gain quantifies how much a model is updated due to new information causing a prediction error.

Researchers commonly define curiosity as a motivational state that stimulates exploration and information seeking to reduce uncertainty (Gruber & Ranganath, 2019; Ivancovsky, Baror, & Bar). When we encounter something unexpected, like a clown at a professional gathering or an unfamiliar problem, it can trigger our curiosity and motivate us to explore novel information, possibly to understand the clown's presence or to attempt to solve the problem (Friston et al., 2017). It has been suggested that curiosity is triggered by strong prediction errors that are seen as indicators of potentially valuable future information (Gruber & Ranganath, 2019). Essentially, curiosity can be characterized as *expected information gain*, where prediction errors arising from unexpected events, such as encountering an unfamiliar problem, provide an estimate of how much a new piece of information (its solution) is expected to minimize these prediction errors, leading to a model update. Note, the more substantial the expected model update, the higher the new information's expected gain.

Creativity involves breaking away from typical expectations and generating novel and useful ideas or solutions (Mednick, 1962). Insight is a fundamental process in creative problem-solving that occurs when a non-obvious problem is solved via a novel solution approach often eliciting an AHA experience (Danek, Williams, & Wiley, 2020; Dietrich & Kanso, 2010). The AHA experience describes the solver's conviction that the solution arrived suddenly, is surprising, certainly correct, involves a feeling of pleasure and internal reward (Kizilirmak & Becker, 2023). Due to its close conceptual proximity to surprise and reward, the AHA! experience has recently been reframed as a combination of different prediction errors tied to different aspects of the problem-solving process, such as the timing of a solution, the solvability of the problem or accuracy of the solution content (Becker et al., 2023; Dubey et al., 2021; Friston et al., 2017). For example, it is assumed that individuals maintain a metacognitive model of their abilities that predicts when they will solve a problem. A prediction error occurs when the solution is found faster than expected, generating a sense of surprise and internal reward (Dubey et al., 2021). In that sense, the AHA experience during *creative problem solving* reflects the *actual information gain*. Actual information gain here describes the (not expected but) actual size of the prediction errors caused by the new piece of information (the solution) leading to a model update and ultimately to a more reliable representation of the world.

In sum, we argued that the shared novelty-seeking basis of *curiosity* and *creativity* can be related to one underlying computational principle of *prediction error minimization*. Curiosity corresponds to an expected gain (model update) for new information that has not yet emerged but whose size is estimated by a current prediction error. In contrast, the AHA experience in creative problem-solving corresponds to the actual gain (model update) of new information that has just become available resulting in a prediction error. In reinforcement learning and the predictive coding theories, this principle has been associated with several other phenomena, such as perception, decision making under uncertainty, memory and reversal, habit or reward-based learning (Friston et al., 2017; Glimcher, 2011). Considering Ivancovsky et al.'s effort to reconcile creativity and curiosity through a common novelty-seeking basis, we believe that this computational principle represents an important perspective for further consideration.

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Computational models of intrinsic motivation for curiosity and creativity

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Abstract

We link Ivancovsky et al.'s novelty-seeking model (NSM) to computational models of intrinsically motivated behavior and learning. We argue that dissociating different forms of curiosity, creativity, and memory based on the involvement of distinct intrinsic motivations (e.g., surprise and novelty) is essential to empirically test the conceptual claims of the NSM.

Human and animal behavior is driven not only by extrinsically available rewards like food and money but also by various *intrinsic motivations*, such as the desire to experience novelty or surprise (Gottlieb & Oudeyer, 2018; Modirshanechi et al., 2023b). Curiosity and creativity are two modes of cognitive processing where such intrinsic motivations have a significant influence. Ivancovsky et al.'s novelty-seeking model (NSM) creates a valuable conceptual link between these intuitively related modes, and divides the shared cognitive processes underlying curiosity and creativity into four phases (Ivancovsky et al.). However, the model's high-level conceptual nature makes it challenging to give quantitative explanations and derive experimentally testable hypotheses. To address this problem, we relate each of the four phases of the NSM to *computational models* of intrinsically motivated behavior and learning. We discuss (i) in which ways computational models *support or contradict* the NSM's core claims, and illustrate (ii) how computational models make the conceptual explanations and predictions of the NSM *empirically testable*.

First, the NSM posits that curiosity and creativity share brain networks and mechanisms to *detect* "novelty," either in the external space of sensory stimuli (curiosity) or in the internal space of associations (creativity). Second, these shared mechanisms *initiate downstream processing* of the "novel" stimulus or association (Ivancovsky et al.). However, although Ivancovsky et al. use "novelty" as a general notion, distinct intrinsic motivations contributing to curiosity (e.g., novelty, surprise, information gain) are mathematically well-defined (Barto et al., 2013; Modirshanechi et al., 2022), have different neural signatures (Akiti et al., 2022; Morrens et al., 2020; Xu et al., 2021; Zhang et al., 2022), and are triggered by different statistical regularities of the task or environment (Maheu et al., 2019) (see Modirshanechi et al., 2023a, for a review). For example, novelty signals are triggered by *unfamiliar* stimuli and situations, both when the unfamiliarity is expected and when it is unexpected (Homann et al., 2022). Surprise signals, on the contrary, arise in the face of *unexpected* stimuli, both familiar and unfamiliar ones (Zhang et al., 2022). In line with that, different neuromodulatory signals are thought to communicate expected versus unexpected novelty or uncertainty (Schomaker & Meeter, 2015; Yu & Dayan, 2005); and computational models suggest different network mechanisms for the detection of novelty and surprise (Barry & Gerstner, 2024; Schulz et al., 2021). Despite the partial overlap in the processing of novelty and surprise (Zhang et al., 2022), we can thus not simply speak of "novelty" detection as a homogeneous process as assumed in the NSM. When empirically testing shared neural mechanisms of curiosity- and creativity-related signal detection and downstream processing, we should therefore consider how the neural correlates of curiosity and creativity may vary across environments and experimental tasks.

Third, the NSM proposes that both curiosity and creativity require a balance of exploratory and exploitatory states of mind (SoM), and that this balance is mediated by cognitive control processes. This NSM prediction agrees with *reinforcement learning-*

based (RL) models that arbitrate between *intrinsic* motivations (curiosity/exploratory SoM) and *extrinsic* motivations (reward/exploitatory SoM) (Modirshanechi et al., 2022; Puigdomènech Badia et al., 2020). Importantly, these RL models quantify the respective contributions of exploration and exploitation to behavior, and allow us to test which mechanisms regulate the trade-off between the exploratory and exploitatory states. For example, a recent model that arbitrates exploration and exploitation based on the agent's reward optimism (Modirshanechi et al., 2022) provides a concrete computational implementation of Ivancovsky et al.'s conceptual links between curiosity and the SoM dimension of openness to experience. We propose that this modeling approach is a useful tool to experimentally validate links between curiosity/creativity and different SoM dimensions as suggested by the NSM.

Lastly, a central component of the NSM is the bidirectional link between memory and curiosity/creativity (Ivancovsky et al.). However, there are different forms of memory and distinct *synaptic learning rules* that are influenced by intrinsic motivational signals (*three-factor learning rules*; Gerstner et al., 2018; Lisman et al., 2011). Although we agree with the bidirectional link between curiosity/creativity and memory systems, we propose that the respective memory system with which curiosity and creativity engage could differ (e.g., episodic vs. recognition memory). More importantly, distinct forms of curiosity and creativity may link to different learning rules and roles of memory. For example, novelty is particularly important for initial memory formation (Duszkiewicz et al., 2019; Priestley et al., 2022), whereas surprise, triggered by the violation of known rules and expectations (Barto et al., 2013; Xu et al., 2021; Zhang et al., 2022), might be more important for targeted memory updates (Gershman et al., 2017). Another relevant distinction that the NSM is currently abstracting is between (i) memory systems that support the *detection* of intrinsic motivational signals and (ii) memory systems that are *downstream targets* of curiosity/creativity-related signals. These memory systems may – but do not have to – be identical. For example, novelty detection relies on state representations in *sensory areas* and *recognition memory* (Bogacz & Brown, 2003; Homann et al., 2022), but downstream novelty signals are also involved in updating *semantic or episodic memories* (Duszkiewicz et al., 2019; Priestley et al., 2022; Wittmann et al., 2007). To empirically determine how memory is shared by curiosity and creativity, it is necessary to experimentally test how different memory systems are involved at each stage and in each type of curiosity/creativity-related processing.

To conclude, we illustrated how the *high-level cognitive* NSM framework relates to *concrete computational models* of intrinsically motivated behavior and learning. Although computational models and the NSM align on the general structure of curiosity- and creativity-related processing, computational models suggest important distinctions within each phase of the NSM. In particular, different forms of curiosity and creativity arising from the contribution of distinct intrinsic motivational signals, like novelty and surprise, could differ in the specifics of how they are detected, signaled to downstream targets, and interacting with memory systems. Linking the NSM to computational models is thus a necessary step to empirically test the NSM's conceptual predictions and gain insights into the neural correlates and network mechanisms underlying curiosity and creativity.

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On the dual nature of creativity: Same same but different?

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Abstract

The creativity literature is replete with dualistic constructs, suggesting shared mechanisms but also tempting overinterpretation of their interrelations. An explicit list of relevant concept associations indicates substantial commonality, yet also exposes certain inconsistencies. Dual-process accounts (A and B is relevant) hold promise in resolving discrepancies to the extent that we understand the relative contributions and conditions of A and B.

Creativity research has substantially progressed over the last few decades by amassing findings of how creativity is related to other psychological constructs. The target article by Ivancovsky et al. adds to this work by reviewing relevant literature and proposing novelty seeking as a shared mechanism underlying creativity and curiosity. This claim is substantiated with an extensive review suggesting similar correlates of both constructs across diverse literatures. Reading the target article, it occurred to me that what the authors have done is to perform a "mental factor analysis" on the correlates of creativity and curiosity to extract the factor explaining most shared variance. Identifying underlying factors and mechanisms that describe observations in a more parsimonious way is a central principle of science; however, this endeavor can run risk of oversimplifying matters by being selective in what evidence is considered or being overinclusive in its interpretation (Benedek & Jauk, 2014). Hence, the question arises whether dualistic constructs, which are very popular in the creativity literature, refer to the same underlying factors, or not.

The extensive synthesis of the target article inspired me to explore what dual constructs are commonly associated in the creativity literature. Table 1 lists constructs distinguishing complemental or opposing concepts mentioned by this review as well as by other works (Baas, De Dreu, & Nijstad, 2008; Boot, Baas, van Gaal, Cools, & De Dreu, 2017; Campbell, 1960; De Dreu, Baas, & Nijstad, 2008; Kounios & Beeman, 2014; Neuberg & Newsom, 1993; Smallwood & Schooler, 2015; Troyer, Moscovitch, & Winocur, 1997; Zuckerman, 1984). Concepts listed in column A are often considered related whereas constructs listed in B are commonly considered distinct or opposing to those in A. The table further organizes constructs by overarching themes such as creative thinking, its neuroscientific basis, neophile traits and states (Griffin, 2016), motivation and moods, cognitive processes including (memory, attention, and cognitive control), and psychopathology. Aligning constructs in this way is helpful to uncover underlying, implicit assumptions and to eventually identify new links but also potential inconsistencies. It struck me that we tend to use different, sometimes vague labels for largely the

Table 1 (Benedek). Common dualistic constructs (distinguishing complemental or opposing concepts A and B) in creativity research: Are they (all) related?

Constructs	Concept A	Concept B
Creative thinking		
Thinking mode	Divergent thinking	Convergent thinking
Ideation stage	Generation	Evaluation (elaboration)
Response quality	*Novelty*, originality	Usefulness, *effectiveness*
Neuroscience		
Brain network	DMN	ECN
Neurotransmitter	*Striatal* dopamine	*Prefrontal dopamine*
Neophilia		
Openness	High	Low
Curiosity type	Diverse	Specific
Curiosity motive	Interest	Deprivation
Novelty seeking	Open-ended	Goal-directed
Stimulation	*Sensation seeking*	*Sensory avoidance*
Uncertainty	Tolerance for uncertainty	*Need for closure*
Ambiguity	*Tolerance for ambiguity*	*Need for structure*
Motivation/mood		
Regulatory focus	Approach	Avoidance
Regulatory style	Intrinsic	Extrinsic
Decision making	Risk taking	*Harm avoidance*
Hedonic tone	Positive mood	Negative mood
Search (memory)		
Foraging	Exploration	Exploitation
Retrieval	*Switching*	*Clustering*
Pathway	*Flexibility*	*Persistence*
Attention		
Attention focus	Defocused	Focused
Perception focus	Global	Local
Thought	Broad	Narrow
Sensory gating	Leaky	*Selective*
Control		
Dual process	*Type 1*	Type 2
Level of control	Spontaneous, associative, undirected, bottom-up	Controlled, deliberate, goal-directed, top-down
Evolutionary mechanism	*Blind variation*	*Selective retention*
Process/experience	*Insight*	*Analytical*
Executive control	Disinhibition	Inhibition
Task focus	*Mind wandering*	*On task*

(*Continued*)

Table 1 (*Continued.*)

Constructs	Concept A	Concept B
Psychopathology		
Subclinical	Distractibility	Perseveration, rumination
Clinical	Schizophrenia	Autism

Note: Concepts in italics were not considered in this context in the target article.

same thing (e.g., defocused, broad, global attention), but then again, we are also very generous in presuming tight relationships across different constructs, together known as the *jingle-jangle fallacy* (Kelley, 1927). Importantly, although positive associations have been assumed between many constructs in A, it does not seem to work well for them all.

For instance, the target article as well as other works assume that idea generation versus evaluation are related to activation of the default mode network (DMN) and executive control network (ECN), and spontaneous versus controlled forms of thought, respectively. However, on the one hand, recent work suggests that episodic simulations associated with DMN structures also contribute to idea evaluation (Benedek, Beaty, Schacter, & Kenett, 2023; Ren et al., 2020). On the other, there is abundant evidence linking idea generation to executive control (Benedek & Jauk, 2019), as it involves core- and metacognitive control processes associated with overcoming prepotent responses and cognitive fixation as well as with finding and implementing goal-directed strategies (Lebuda & Benedek, 2023; Smith & Blankenship, 1991); in contrast, the empirical evidence on the association between idea evaluation and cognitive control is still relatively scarce (but, see, Benedek et al., 2016; Karwowski, Czerwonka, & Kaufman, 2020). Similarly, exploration versus exploitation of cognitive spaces corresponds to switching versus clustering tendencies (Troyer et al., 1997), with the former being related to higher cognitive control (Ovando-Tellez et al., 2022; Rubinstein, Meyer, & Evans, 2001) – again opposing a simple exploration–spontaneity relationship.

It seems that Ivancovsky et al. also came to the conclusion that cognitive control does not fit well with the other constructs, which motivated them to eventually propose a two-dimensional model with exploration/exploitation and inhibition/disinhibition (akin to cognitive control) as independent factors. This makes sense in my view, although it was not clear why convergent thinking ended up on the exploration side. Another important move was to acknowledge that creativity and curiosity are strongly associated with A, but actually rely on both A *and* B. This view is consistent with long-standing dual-process models that emphasized the interplay of exploration and exploitation modes (Hart et al., 2018; Hills, Jones, & Todd, 2012) also known as flexibility versus persistence pathways to creativity (De Dreu et al., 2008; Nijstad, De Dreu, Rietzschel, & Baas, 2010), as well as arguing for the relevance of an interplay between spontaneous and controlled processes (Benedek & Jauk, 2018; Sowden, Pringle, & Gabora, 2015; Zabelina & Robinson, 2010). Future research is challenged to study the very nature and conditions of these interplays in more detail to avoid oversimplistic conclusions such as that everything is important for creativity. Another question refers to the actual independency of exploration/exploitation with the level of cognitive control, which appears supported by recent work showing that clustering and switching can occur fast and slow (Ovando-Tellez et al., 2023). The list in Table 1 may prove useful in reconsidering our theorizing on these dualisms toward enhancing our understanding of the nomological network of creativity (Kenett et al., 2020).

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Dissecting the neuroanatomy of creativity and curiosity: The subdivisions within networks matter

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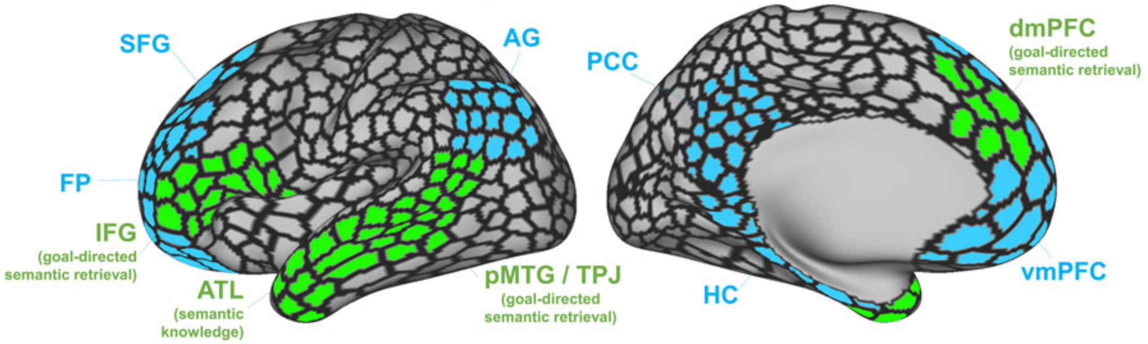
Abstract

Ivancovsky et al. argue that the neurocognitive mechanisms of creativity and curiosity both rely on the interplay among brain networks. Research to date demonstrates that such inter-network dynamics are further complicated by functional fractionation within networks. Investigating how networks subdivide and reconfigure in service of a task offers insights about the precise anatomy that underpins creative and curious behaviour.

Researchers generally agree that creative ideation needs to fulfil two criteria (Sternberg & Kaufman, 2010) – originality and effectiveness. *Originality* pertains to combining pre-existing concepts in novel and unique ways, while *effectiveness* relates to whether the new combination of old ideas can satisfactorily solve a problem or appropriately fit into a context by considering relevant constraints. These definitions naturally map onto distinct stages of cognitive processing (Benedek, Beaty, Schacter, & Kenett, 2023) – idea generation (forging novel links between concepts) and idea evaluation (assessing whether the new idea is goal-relevant or sufficiently innovative). Neuroimaging evidence has demonstrated that the two stages rely on distinct dynamics amongst several brain networks – for example, the default, salience, and executive control networks (Beaty, Benedek, Silvia, & Schacter, 2016). The theory paper by Ivancovsky et al. comprehensively reviewed the neuroimaging literatures of creativity and curiosity, identified multiple similarities in the neurocognitive mechanisms of the two, and proposed a novelty-seeking model to account for the commonalities between creative pursuits and curiosity-driven behaviour.

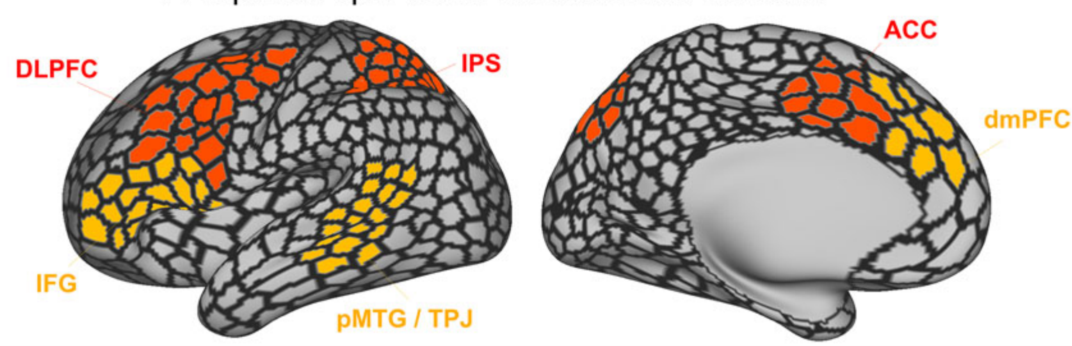
We agree with Ivancovsky et al.'s proposal that both creativity and curiosity are multidimensional constructs that entail multiple stages of cognitive processing and depend on the interaction between multiple brain networks. One important caveat, however, should be considered – decades of connectomic research have demonstrated that the default network and executive network are both highly heterogeneous systems, consisting of multiple subnetworks that differ with respect to their functional tunings and connectomic fingerprints. For example, research from our laboratories and other research teams have shown that the default network is functionally fractionated into (at least) two subnetworks – one is more associated with semantic memories, evaluative cognition and convergent thinking, while the other is more associated with episodic memories, free association, simulating hypothetical scenarios and divergent thinking (e.g., Chiou, Humphreys, & Lambon Ralph, 2020, 2023a; Krieger-Redwood et al., 2023; Zhang et al., 2022). As illustrated in Figure 1(A), the "semantically oriented" subnetwork consists of the inferior frontal gyrus, anterior temporal lobe, temporoparietal junction and dorsomedial prefrontal cortex, while the "episodically oriented" subnetwork consists of the ventromedial prefrontal cortex, posterior-cingulate/retrosplenial cortex, hippocampi and angular gyri. This "semantic *versus* episodic" dissociation topographically accords with conventional taxonomy of subregions within the default network (e.g., Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010) – the semantic subnetwork overlaps substantively with the dorsomedial subsystem, while the episodic subnetwork overlaps significantly with the medial-temporal and core subsystems. Such dissociation was not only observed in the subnetworks' tuning for task contexts but also in intrinsic connectivity under task-free situations (e.g., Yeo et al., 2011). Like the default network, the brain's executive control network can also be functionally split into (at least) two subnetworks. One is associated with exerting cognitive control over memory-based representations, including both semantic memories and episodic memories (e.g., Chiou, Jefferies, Duncan, Humphreys, & Lambon Ralph, 2023b; Gao et al., 2021; Vatansever, Smallwood, & Jefferies, 2021), while the other is associated with exerting control over perception-based representations (e.g., Assem, Glasser, Van Essen, & Duncan, 2020, 2022; Branzi & Lambon Ralph, 2023). As shown in Figure 1(B), the subnetwork biased towards the control of memory includes the inferior frontal gyrus and the posterior mid-temporal gyrus, while the subnetwork biased towards controlling perception includes a large swath of the dorsolateral prefrontal cortex, middle/anterior cingulate cortex and intraparietal sulcus. Furthermore, connectivity evidence shows that regions biased for mnemonic/semantic control tightly couple with the default network, while regions biased for perceptual control closely link with the visual cortex and dorsal-attention network (Dixon et al., 2018).

(A) Bipartite split within the default network



subnetwork	constituent regions	preferred memory	preferred tasks	potential role in creativity
semantic network	bilateral anterior temporal lobes (ATL) left inferior frontal gyrus (IFG) left post. mid-temporal gyrus (pTMG) left temporoparietal junction (TPJ) dorsomedial prefrontal cortex (dmPFC)	semantic memory	convergent thinking analytical thinking evaluative cognition semantic decision problem solving	ATL may provide the semantic contents for idea generation IFG, pMTG, TPJ, dmPFC may be involved in idea evaluation
episodic network	bilateral angular gyri (AG) bilateral hippocampi (HC) post.-cingulate/retrosplenial cortex (PCC/RSC) ventromedial prefrontal cortex (vmPFC) frontal pole (FP) & superior frontal gyrus (SFG)	episodic memory	episodic retrieval social cognition theory of mind mental simulation free association	All these areas may be involved in retrieving past episodes or simulating imagined scenarios to support creativity

(B) Bipartite split within the executive network



subnetwork	constituent regions	preferred tasks	potential role in creativity
Memory control (a.k.a. semantic-control network)	left inferior frontal gyrus (IFG) left post. mid-temporal gyrus (pMTG) left temporoparietal junction (TPJ) dorsomedial prefrontal cortex (dmPFC)	All these areas are involved in goal-directed retrieval of semantic memory; in addition, the IFG is involved in episodic retrieval	This network may be involved in idea evaluation, comparing the suitability or efficacy of ideas
Perception control (a.k.a. multiple-demand network)	dorsolateral prefrontal cortex (DLPFC) bilateral intraparietal sulci (IPS) middle/anterior cingulate cortex (ACC)	All these areas are involved in goal-directed operation on perceptual representations (e.g., visual search or visual/auditory n-back)	This network may be involved in directing attention to relevant perceptual input during creation

Figure 1 (Chiou et al.). (A) The bipartite split within the brain's default network. (B) The bipartite split within the brain's executive network. Note that the network affiliations of the IFG, left pMTG/TPJ and dmPFC are fluid – while these regions are classified as nodes of the default network during the resting-state, they can also be involved in controlled retrieval of semantic/episodic memory in task situations.

Given this functional heterogeneity, we suggest that Ivancovsky et al.'s proposal that "*creativity relies on the interaction amongst brain networks*" and "the *generation and evaluation of creative ideation relies respectively on the default and executive network*" is under-specified. Further research is needed to pinpoint how the division of default and executive systems into subnetworks enables distinct facets of creativity. Recently, we have begun to unravel how different types of creative ideas are underpinned by distinct component regions of these networks. Using a multivariate regression approach with functional MRI, we showed that when creativity is built on semantic memory, it is associated with greater activity in regions involved in semantic retrieval (the inferior frontal gyrus and dorsomedial prefrontal cortex) while minimally engaged those regions for episodic memory; on the other hand, when creativity is built on episodic memory, it is associated with greater activity in regions involved in episodic memory (the retrosplenial cortex) while minimally recruited those regions for semantic memory (for details see Krieger-Redwood et al., 2023). Particularly, when participants attempted to produce creative links between word-pairs that are barely semantically related (e.g., marigold and sphinx), the brain reacted to such a semantically challenging situation with extensively distributed activation spread across the semantic subnetwork (inferior frontal gyrus) and executive network (dorsolateral prefrontal cortex and anterior cingulate cortex), potentially reflecting the mental manoeuvre between paying attention to text and recombining semantic concepts. Interestingly, such widespread,

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cross-network activation disappeared when participants produced creative links between closely related words (e.g., flight and holiday); instead, this situation elicited activation of the retrosplenial cortex, which dovetailed with participants' report that they inclined to episodic retrieval in this context (e.g., recalling a recent trip).

Taken together, multiple evidence consistently indicates that both semantic and episodic memory contribute to the emergence of creative ideas (Benedek et al., 2023). Under different circumstances, the brain employs distinct cognitive tactics and neural machineries to engender creative ideas, depending on whether semantic concepts are assembled in a novel way or episodic memories are used to create quirky contents.

While the novelty-seeking model proposed by Ivancovsky et al. nicely integrates two forms of introspective processes, creativity and curiosity, with various cognitive processes and brain networks, it remains to be clarified how their model fits with evidence for the fractionation of networks into subparts and their flexible network-wide reconfiguration to suit different contextual requirements. Although fractionations and reconfigurations complicate current theories about the neural substrates of creativity, these considerations provide a more truthful description of the underlying mechanisms. A fruitful direction for future research is to consider the fusion and fissure within and between networks, which can provide valuable insights regarding how the brain implements flexible cognition.

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Is a wandering mind a novelty-seeking mind? The curious case of incubation

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Abstract

The Novelty-Seeking Model can explain incubation's effect on creativity by assuming an adaptive decision threshold. During an impasse, the threshold for novelty becomes too high and biased to previous neural activity, hindering progress. Incubation "resets" this threshold through attentional decoupling, allowing for spontaneous ideas to emerge from subsequent mind wandering or other activities that attract attention, facilitating progress.

Ivancovsky et al. propose that curiosity and creativity "are manifestations of a unified process that underlies novelty-seeking" (p. 45). They suggest that curiosity and creativity reinforce each other such that the more curious and creative a person is, the more attuned they become to novel stimuli. This heightened sensitivity to novelty, the authors argue, is a result of being in a novelty-seeking mode, which raises neural activity associated with (spontaneous) mental events above a certain decision threshold. This process might explain "how certain stimulation can attract our attention and be perceived as novel and interesting" (p. 45). We propose how this idea can be expanded to the state of incubation, in which people tend to refrain from deliberate thoughts about a task or problem and instead do something else and/or let their minds wander.

Incubation is an interesting state in terms of the Novelty-Seeking Model. Creative thinking requires people to flexibly shift along a continuum of exploitation (which is linked to goal-directed, convergent thinking, specific curiosity, and deprivation) to exploration (which is linked to open-ended, divergent thinking, diverse curiosity, and interest) to arrive at outcomes that are useful and original. When attention shifts from being focused to becoming de*focused*, irrelevant information is allowed to "leak in" (Ivancovsky, Baror, & Bar). Incubation, however, appears to be even further along this continuum: attention becomes de*coupled* from the task at hand, and often refocused on something else (Ritter & Dijksterhuis, 2014), such as self-generated cognition (e.g., mind wandering; Faber, Krasich, Bixler, Brockmole, & D'Mello, 2020). We argue that in addition to focused and defocused attention, decoupled or refocused attention might play an important role in novelty-seeking that could explain the often-reported positive relationship between decoupled processes such as incubation and mind wandering on the one hand, and creativity on the other.

Indeed, many famous anecdotes support this strategy's effectiveness for overcoming impasse (Wallas, 1926). Mathematician Poincaré, for example, had one of his most important theoretical breakthroughs during a geological excursion, because, as he claimed, "the changes of travel made me forget my mathematical work" (Poincaré, 2022, p. 387). When an impasse occurs, the threshold for what is novel and interesting has become too high and too biased to previous neural activity to make progress (Beda & Smith, 2022; Gauselmann, Frings, Schmidt, & Tempel, 2023). In line with the Novelty-Seeking Model, during incubation, this threshold might be lowered adaptively, allowing for ideas that arise spontaneously to attract attention. Lowering the threshold might enhance the salience of spontaneous ideas. This increases the probability that one can make progress after an impasse, but also comes at the cost of accuracy. In turn, when progress is being made the threshold is raised to restore accuracy accordingly, through more deliberate modes of creative thought.

The idea of such an adaptive threshold finds its origins in adaptive gain theory, which may offer further insight into how incubation supports creativity. This theory postulates that the dynamic shift between focus and defocus in response to changing environmental demands is regulated by the locus coeruleus norepinephrine system (Aston-Jones & Cohen, 2005). Increases in tonic norepinephrine (NE) – the slow release of NE – boosts overall signal strength in neural circuitry, enabling sensitivity to novel and task-irrelevant information. Phasic NE – fast bursts of NE release – enhances responses to salient events (Mittner, Hawkins, Boekel, & Forstmann, 2016). In view of the Novelty-Seeking Model, moderately heightened tonic NE may help facilitate creativity through defocusing while maintaining a suitable level of alertness (de Rooij, Vromans, & Dekker, 2018), whereas phasic responses facilitate focus in response to salience (Salvi, Simoncini, Grafman, & Beeman, 2020), which can help to select an idea as a basis for further creative thinking (de Rooij, 2023; Simonton, 2023).

Attentional decoupling is facilitated by an upshift in tonic NE, which enhances neural gain and functional connectivity within and between networks, allowing for the brain to go into a more exploratory mode. In addition, when tonic NE levels become high, it reduces phasic responses to the extent that attentional decoupling occurs (Mittner et al., 2016). The upshift in tonic NE in response to an impasse might therefore facilitate the "reset" needed to reduce the bias to previous neural activity that has led to the impasse. We suggest that this upshift in tonic NE also effectively lowers the threshold for what is novel and interesting. The behaviors that a person subsequently engages in during incubation, whether it is letting the mind wander or refocusing on something else, then may promote the attentional shift toward spontaneous ideas, which are more likely to become salient due to the lowered threshold.

Behaviorally, this resonates with our own work, in which we have recently observed that there is indeed a bias such that ideas that arise spontaneously are perceived as more novel than those that are deliberate, even if objectively, there is no difference (de Rooij, Atef, & Faber, 2023). We would therefore like to argue that the activation threshold might be dynamic: when one is stuck on a problem and searching for a specific idea, the threshold might be higher, allowing for selectivity. Incubation might provide a "reset" of the threshold, allowing for (potentially not particularly novel or interesting) ideas to attract attention such that progress can be made. With this proposed theoretical expansion of the Novelty-Seeking Model, we aim to capture an important feature of creative idea generation, namely how the dynamic regulation of attention to spontaneous and deliberate thoughts together enables creativity.

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Ignoring the role of reiterative processing and worldview transformation leads to exaggeration of the role of curiosity in creativity

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Abstract

The Novelty-Seeking Model does not address the iterative nature of creativity, and how it restructures one's worldview, resulting in overemphasis on the role of curiosity, and underemphasis on inspiration and perseverance. It overemphasizes the product; creators often seek merely to express themselves or figure out or come to terms with something. We point to inconsistencies regarding divergent and convergent thought.

The Novelty-Seeking Model (NSM) linking creativity and curiosity is useful in broad terms, but it *downplays the complexity of creativity* in ways that lead to overemphasis on the impact of curiosity, and underemphasis on inspiration, reiterative processing, cognitive flexibility, and perseverance. This oversimplification comes through in phrasing such as "increasing the repertoire of possible responses, thus enhancing novel thoughts and actions" (p. 24), which implies that creativity is merely a matter of having a large repertoire of available knowledge (raw ingredients). It's *what you do with* that knowledge (how you turn the raw ingredients into a cake) that makes you creative (Gabora, 2002). It is true that creativity "utilizes stored representations in memory to generate novel ones," but there may be thousands of intermediate steps between the stored representations and the novel outcome. These intermediate steps involve recursive reflection on a question or problem by viewing it from different perspectives, a process that has been referred to as *honing* (Gabora, 2017; see also Piffer, 2012). Referring to creativity as "search" implies that the creative idea *already exists* and is waiting to be found, but due to the *reconstructive* nature of memory, and the emergence of new properties when concepts interact, the fruits of creative thought may be different from anything ever stored in memory (Gabora, 2000, 2002, 2010, 2018; Gabora & Ranjan, 2013).

The article *misleadingly implies that the sole goal of creativity is to obtain a novel product*. Creators often merely seek to express themselves, or figure out or come to terms with something; this is why creativity can be therapeutic, and accompanied by a sense of release (Barron, 1963; Forgeard, 2013). The outputs of creative thinking are sometimes discarded, the rationale for this being, "it's the journey that matters." The authors' emphasis on outputs stems from their chosen definition of creativity in terms of the ability to generate new and useful outputs. Elsewhere a process is defined as creative to the extent that it *recalibrates a cognitive model* (Gabora & Bach, 2023). Creative thinking may result in a fresh perspective or outlook that doesn't directly manifest as any particular output but has indirect long-term impacts. By defining creativity in terms of internal change, the proposed framework would be able to explain the above-mentioned therapeutic benefits of creativity, and conversely, why psychotherapy itself can be viewed as a creative process (Ganesh & Gabora, 2022).

In the NSM framework, generative activation and evaluation are presented as distinct phases. We argue that throughout the creative process, one is reiteratively *both* generating (by reflecting on something from a new perspective) *and* evaluating the result (of that particular reflection), for if evaluation were avoided until a later phase, any early misstep could render every sequence of subsequent steps useless. We suspect that (contrary to the article), evaluation may be as spontaneous as generation. The separation of generative activation and evaluation in NSM stems from adopting the view that creators generate as many solutions as possible and then choose the best, a view that is inconsistent with the results of studies of analogy making and artmaking (Carbert, Gabora, Schwartz, & Ranjan, 2014; Gabora & Saab, 2011; Scotney, Schwartz, Carbert, Adam Saab, & Gabora, 2020). Even when a creator generates multiple possibilities (e.g., multiple sketches for a painting) and chooses one, these seemingly distinct possibilities may be just *different ways of expressing a single underlying idea that the creator is wrestling with* (Gabora, 2019; Gabora & Steel, 2022), and in so doing, forging their personal creative style (Gabora, O'Connor, & Ranjan, 2012). These different possible expressions of an ill-defined idea have been modeled as different projections of a superposition state (Gabora, 2017; Gabora & Carbert, 2015).

The authors claim that both divergent thought (DT) and convergent thought (CT) are necessary to produce novel ideas but, according to the definitions for CT and DT in the target article, the best-known creativity tests require only one or the other, for example, the Alternate Uses Task (AUT) (Christensen, Guilford, Merrifield, & Wilson, 1960) requires only DT, and the Remote Associates Test (RAT) (Mednick, 1968) requires only CT. The authors could defend their claim by specifying that only big-C creativity require both modes of thought, and indeed there is evidence for this (Beersma & De Dreu, 2005; Gibson, Folley, & Park, 2009; Kerr & Murthy, 2004). However, defining CT and DT in terms of the number of correct solutions (as in the article) still makes no sense; a problem either has one correct solution *or* it has multiple correct solutions. In addition, it is often noted that earlier responses on DT tasks are less creative than latter ones (Beaty & Silvia, 2012), but if DT is characterized in terms of the number of responses, this is the opposite of what one should expect, because with each response one gives, the number of remaining viable responses decreases by one. Thus, the definitions of DT and CT adopted here would predict that, as creative thought proceeds, one starts thinking more convergently, not more divergently.

These problems can be avoided by defining CT as honing in which *concepts are considered from conventional contexts*, and DT as honing in which *concepts are considered from unconventional contexts* (Gabora, 2019). In this view, the underlying cognitive process is the same in both; that is, in both one is looking at something in a different context. However, the unconventional contexts considered in DT result in widely different conceptions (which get counted as different ideas), while the similar contexts considered in CT result in similar conceptions (which get counted as refinements of the same idea) (Gabora, 2019; Gabora & Steel, 2022; Scotney *et al.*, 2020). (A useful analogy is: DT is like shining light on an object from very different angles, producing differently shaped shadows, while CT is like shining the light from similar angles, producing similar-shaped shadows.) This way of defining CT and DT is consistent with findings that creativity is linked to performance on not just DT tests (Plucker & Renzulli, 1999; Runco, 2014), but also CT tests (Benedek & Neubauer, 2013); creators simply excel at considering things from different, relevant perspectives.

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Toward a causal model of curiosity and creativity

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Abstract

We extend Ivancovsky et al.'s finding on the association between curiosity and creativity by proposing a sequential causal model assuming that (a) curiosity determines the motivation to seek information and that (b) creativity constitutes a capacity to act on that motivation. This framework assumes that both high levels of curiosity and creativity are necessary for information-seeking behavior.

Ivancovsky et al. present a much-needed review of the evidence for the linkage between curiosity and creativity via a shared novelty-seeking mechanism. While the authors' model helps explain the observed correlation between curiosity and creativity across domains, it provides no clear theoretical position on the quality of this link. Here, we attempt to develop such a position by proposing a working mechanism. Specifically, we propose a causal model of how novelty-seeking, and more generally information-seeking behavior, results from curiosity and creativity. We consider curiosity to be a prerequisite for seeking new information and creative thinking styles the capacity to seek new information. In essence, we suggest that two different types of curiosity and two different creative thinking capacities determine the type and degree of information-seeking behavior.

The authors of the target article distinguish between two dimensions lying at the core of the curiosity concept: Broad curiosity and specific curiosity (see also interest vs. deprivation, Litman, 2008; and joyous exploration vs. deprivation sensitivity, Grüning & Lechner, 2023; Kashdan, Disabato, Goodman, & McKnight, 2020). These dimensions can also be distinguished behaviorally as the motivation to gather information versus to generate new information (see first ideas in Bluemke, Engel, Grüning, & Lechner, 2023). This distinction also suggests that there exist at least two types of information-seeking behavior. Specifically, people explore their world to gather new information, which can be referred to as broad curiosity behavior. However, people also actively generate new information in the form of solutions to problems or the result of combining different pieces of information, which would be regarded as specific curiosity behavior.

Ivancovsky et al. show that broad curiosity – the motivation to gather new information – is related to divergent thinking. In contrast, specific curiosity – the motivation to generate new information – is related to convergent thinking. We extend this idea by proposing a casual framework comprising a set of paths leading from curiosity to creativity and on to information-seeking behavior. As shown in Figure 1, we propose that creativity, conceptualized as the capacity for engaging in different styles of thinking, moderates whether curious people can actually engage in information-seeking behavior. While the motivation to gather (i.e., broad curiosity, interest, and joyous exploration) or generate (i.e., specific curiosity, deprivation, and deprivation sensitivity) information is a prerequisite for any information-seeking behavior, it is not sufficient. An individual's creativity, among other moderators (e.g., time resources and cognitive load), determines their ability to follow through on the motivation to seek new information. For illustration, if one is motivated to gather new information about business strategies or the big cats, one's capacity for divergent thinking might primarily guide the degree of information-seeking behavior exhibited, ultimately determining the amount of detail and breadth of information gathered (e.g., leadership do's and dont's or that the cheetah is the fastest big cat). Similarly, an individual who is motivated to generate new information as a means of solving an open problem (e.g., which business strategy to choose for the own company) or combining existing pieces of information (e.g., that another big cat like the lion can generally not catch a cheetah) may only be able to do so within the limits of their capacity for convergent thinking. Information-seeking behavior may not be exhibited if curiosity is low, or if a specific curiosity is high but the corresponding capacity for divergent or convergent thinking is low. For a specific type of information-seeking behavior to be exhibited, both the correct type of curiosity and creativity must be sufficiently high.

With due caution, we note that the sequentiality of a particular type of curiosity or a particular type of creative thinking style in the causal chain toward information-seeking behavior is difficult to argue for per se. With the direction proposed in Figure 1, we follow the conceptual idea that cognitive preparatory processes such as motivation precede the testing of corresponding capacities, such as thinking styles, to result in actual behavior.

Ivancovsky et al. have taken a significant step toward establishing an associative link between curiosity and creativity. In this commentary, we sought to stimulate a way of thinking about the quality of this link with the goal to test which aspects of curiosity and creativity interact in which ways to lead to information-seeking behavior. We propose a testable causal model of the association between curiosity and creativity, in which the effect of the former on actual information-seeking behavior is moderated by the latter. In this regard, we also call for research to distinguish between two different types of information-seeking, namely, gathering and generating information, at the behavioral level. Our model, we hope, takes another step forwarded, inspiring targeted

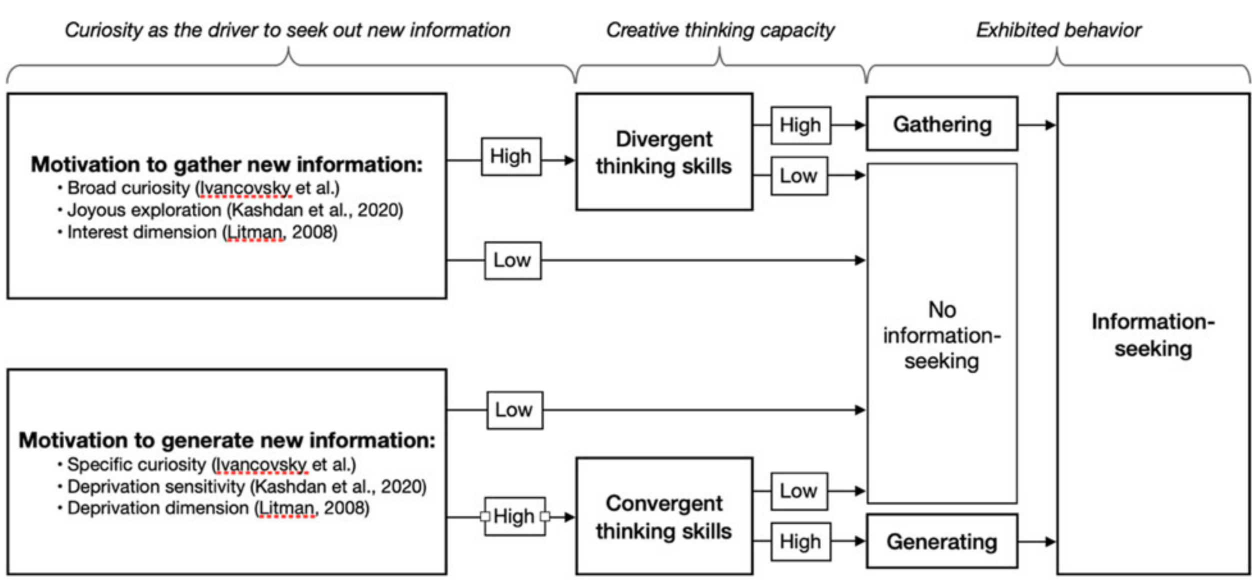

Figure 1 (Grüning and Krueger). Causal model of curiosity, creativity, and information-seeking behavior.

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studies on the quality of the causal relationship between curiosity, creativity, and information-seeking.

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A shared "optimal-level of arousal": Seeking basis for creativity and curiosity

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Abstract

We argue that the phases identified in the novelty-seeking model can be clarified by considering an updated version of the optimal-level of arousal model, which incorporates the "arousal" and "mood changing" potentials of stimuli and contexts. Such a model provides valuable insights into what determines one's state of mind, inter-individual differences, and the rewarding effects of curiosity and creativity.

We commend the authors' effort in bridging exploratory and creative behaviors with the recent findings related to their possible neural correlates. The proposed novelty-seeking model (NSM) includes four phases: affinity, activation, evaluation, and commitment. We would like to extend these points by considering an updated version of the optimal-level of arousal (or stimulation) model (henceforth OLA model), traditionally used to explain the exploration/exploitation continuum, and which has recently been proposed to clarify links between curiosity and creativity (Gustafsson, 2023; Ibáñez de Aldecoa, Burdett, & Gustafsson, 2022). For instance, the idea of novelty seeking as a biological need, as suggested by the authors, and by others (González-Cutre, Romero-Elías, Jiménez-Loaisa, Beltrán-Carrillo, & Hagger, 2020), has been criticized because an excess of novelty may be overstimulating, perceived as noise, and not necessarily evaluated positively. Reframing the need for novelty as a need for an optimal-level of arousal (or stimulation) would address this issue. We specifically suggest consideration of the "arousal" and "mood changing" potential of stimuli and context in explaining the relationship of curiosity and creativity.

The OLA model hypothesizes that exploratory behaviors are mainly used to maintain an optimal level of arousal (Berlyne, 1966; Dember & Earl, 1957; Schneirla, 1959; Zuckerman, 1994). Incorporating the concepts of "arousal" potentials of stimuli and contexts into the NSM can provide valuable insights into what determines affinity and activation. In fact, assuming that processing stimuli is costly, the arousal potential of the context in which the stimulus is embedded (i.e., its novelty, complexity, intensity, or surprise features) may have a determining role on exploratory behaviors. For instance, by decreasing overall stimulation, familiar contexts should favor exploration of novelty to get closer to our optimum. In contrast, by increasing overall stimulation, novel contexts should favor exploration of familiarity.

In the same vein, mood changing potentials of stimuli and context can also affect exploratory behaviors by modifying the cognitive resources available and the resulting arousal potentials of encountered stimuli and contexts. For instance, it is well documented that a comforting social environment or a happy mood decrease attraction toward familiarity and favor approach toward novelty in both human (Crockenberg & Leerkes, 2004; de Vries, Holland, Chenier, Starr, & Winkielman, 2010) and non-human animals (Coleman & Mellgren, 1994; Dally, Clayton, & Emery, 2008; Forkman, 1991; Moretti, Hentrup, Kotrschal, & Range, 2015; Stowe, Bugnyar, Heinrich, & Kotrschal, 2006; Visalberghi & Addessi, 2009; Voelkl, Schrauf, & Huber, 2006). In contrast, physiological stressors tend to result in withdrawal from novelty/complexity and approach toward familiarity (Griebel, Belzung, Misslin, & Vogel, 1993; Heinrichs & Koob, 1992; Shors & Wood, 1995).

These findings are relevant for the current model as they relate both to the effect of arousal and to the broadening or narrowing of thinking mentioned by the authors in the State of Mind (SoM) Framework. The "Regulatory Focus Theory," a well-established theoretical model, offers a clearer understanding of the mechanisms underlying these phenomena (Higgins, 1997). This model identifies a "promotion focus" motivation – in which people focus on growth – and a "prevention focus" motivation – in which people focus on maintaining security. Promotion state has been linked to the broadening of mental categories by adopting a more global processing style, while prevention state has been linked to their narrowing (Fredrickson, 2001; Friedman & Förster, 2001). Accordingly, broadening mental categories increases the likelihood that new stimuli integrate pre-existing representations and appear familiar, which would decrease their arousal potential (Förster, Marguc, & Gillebaart, 2010). For these reasons, novelty is more attractive in a "promotion" state while familiarity is more appealing in a "prevention" state of mind (Gillebaart, Förster, & Rotteveel, 2012).

Besides the state of mind, the optimal-level of stimulation model considers any factors affecting the cognitive resources available to predict exploration outcomes. Age is one of such major factors. For instance, while newborns explore familiarity more (Cernoch & Porter, 1985; Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995; Schaal, 2005), older infants and young children are more attracted toward novelty and complexity (Dovey, Staples, Gibson, & Halford, 2008; Greenberg & O'Donnell, 1972; Hunter, Ames, & Koopman, 1983). Such transition would reflect the broadening of mental categories and cognitive resources acquired through experience and brain maturation (Brennan, Ames, & Moore, 1966; DeLoache, Rissman, & Cohen, 1978; Greenberg & O'Donnell, 1972).

As stated in the NSM, acquiring information through curiosity and creativity can be an intrinsically rewarding state in the evaluation phase of their model. The OLA model would provide here some mechanistic explanation of why this is so. In fact, in order to trigger the intrinsic motivation to explore, a stimulus must have a positive emotional valence which can also result from its arousal potential in addition to previous reinforcements. For instance, a very simple stimulus, usually perceived as boring, could get a very positive valence for an understimulated individual in an environment providing few affordances.

Interestingly, such stimuli can also come from internal physical or mental processes. For example, a bored person could engage in repetitive fidgeting movements, active thinking, daydreaming, or creative activities for the sake of the pleasurable stimulation such activity would provoke by itself. We argue that considering creative behaviors as attempts to produce our own stimulation in order to get closer to our optimal level of arousal could be key to relate arousal, curiosity, and creativity. It can help clarify why an exploratory SoM may enable some form of creativity to arise while an exploitatory SoM would promote narrow and specific exploration as stated in the target article. According to such a view, low arousal should favor both diversive curiosity to get more stimulation and divergent thinking to complexify one's environment. In contrast, high arousal would favor both specific curiosity and convergent thinking as both are aimed at solving problems and simplifying one's environment (Gustafsson, 2023).

The updated OLA model, by taking into account the "arousal" and the "mood changing" potential of stimuli and context, sheds new light on the NSM model phases. For this reason, we advise tinkering the authors' novelty-seeking model into an optimal-level of arousal seeking model, which would allow for clearer explanation of curiosity and creativity relationships.

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Novelty seeking is neither necessary nor sufficient for curiosity or creativity, instead both curiosity and creativity may reflect an epistemic drive

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Abstract

Novelty is neither necessary nor sufficient to link curiosity and creativity as stated in the target article. We point out the article's logical shortcomings, outline preconditions that may link curiosity and creativity, and suggest that curiosity and creativity may be expressions of a common epistemic drive.

According to the target article, humans (1) detect novelties that (2) instill curiosity. Then (3) the curious mind enriches memory by encoding the novelty. Finally, (4) memories thus constructed are recombined in creativity leading to new actions or thoughts. We provide a critique against all four causal links, and demonstrate that curiosity and creativity are typically unrelated.

Curiosity does not demand expected novelty

Novelty involves epistemic expectations about what is more or less likely to occur ontologically (uncertainty about existence) or within the bounds of a specific contextual state (e.g., uncertainty about action outcomes). Studies involving trivia questions demonstrate that ontological uncertainty can instill curiosity, but only when some preconditions are met such as in the presence of prior domain interest, or that guesses are extrinsically rewarded (Dubey & Griffiths, 2020; Fastrich, Kerr, Castel, & Murayama, 2018). However, nonnovel environments with regularly occurring but uncertain states and outcomes are also powerful stimulators of curiosity, demonstrated by studies involving simple decisions in lotteries, and sensorimotor control tasks (Holm, Wadenholt, & Schrater, 2019; Kobayashi, Ravaioli, Baranès, Woodford, & Gottlieb, 2019; Van Lieshout, Vandenbroucke, Mu, & Cools, 2018). In fact, simply needing to refresh our memories can be a potent curiosity inducer as in the urge to look up an actor's name you forgot when recounting a movie. In general, our environments and memories are replete with novelties, uncertainties, and missing features and we are indifferent to most of them. What suffices to instill curiosity remains unknown, but novelty is neither sufficient nor necessary.

Curiosity-driven learning does not need to expand memory

Curiosity often targets very restricted knowledge variables such as the performance in computer games (Holm et al., 2019; Ten, Kaushik, Oudeyer, & Gottlieb, 2021; Van Lieshout et al., 2018), or information seeking in social media (Zahoor, 2022). These activities may become obsessive yet satisfy curiosity, and may even lead to addiction-like behavior (Hsu, Wen, & Wu, 2009; Weinstein, 2010). This type of curiosity-driven learning might even gate out the acquisition of new knowledge by expending cognitive resources and time improving efficiency in a narrow domain, which arguably constitutes an exploitative rather than exploratory pursuit.

Novel memories do not need to promote creativity

Curiosity learning and novel memories often result from observation learning. Imagine that monkey A watches monkey B perform a novel task, and later monkey A recalls the event and solves the task via imitation. While for monkey A, this constitutes a novel action stemming from a curiosity encoded memory, its creativity is sorely limited. More generally, enriching memory with more solutions does not imply coming up with a *better* solution. A football team with 11 great forwards is probably not a great team. Reusing stored solutions is exactly exploitation, even if the information is subjectively novel and encoded under curiosity. Instead, creativity requires a *recombination of memories* – and that requires memories that meaningfully overlap and are decomposable. Curiosity-induced imitation learning is ubiquitous but excludes the meaning (intent/reasons/semantics) for the actions, which limits the ability to decompose (identify steps) and to find overlaps. In fact, generalization in learning has been shown to be sharply limited in imitation learning without structured training that provides overlapping alternative solutions (Braun, Mehring, & Wolpert, 2010; Wolpert & Flanagan, 2016).

Creativity does not imply curiosity

Although curiosity need not lead to creativity as the authors claim, they could still be linked if, when creativity occurs, curiosity is implicated. Unfortunately, this backward implication is false because (1) the presence of creativity does not imply enriched (novel) memories. Any old memories suffice as long as their *recombination* is novel and valid. (2) Enriched memories do not imply curiosity because curiosity is not necessary for learning. (3) The presence of curiosity neither does require novelty as outlined above nor is (4) novelty detection a necessary precondition for instilling curiosity.

Conditions for curiosity to promote creativity

Although curiosity and creativity are independent in many conditions, the analysis above suggests they may be related when: (1) Curiosity results in improved and enriched memory representations that (2) lead to valid recombinations. But even with these conditions met, the reason for a common underlying principle operating within the intersection of the conditions seems unclear, other than novelty seeking is an inadequate basis. To illustrate what creativity entails, consider Stoffel the honey badger, a talented escape artist whose incessant need for freedom exceeds the repeated efforts of his keepers (BBC, 2014). But being free is a poorly defined environmental goal state because it does not indicate a unique point that is required for a typical control system. We need to invoke higher order internal goal states to account for Stoffel's (and other creative creatures') behavior in which "freedom" can be construed as well-defined (internal) goal states in an abstract epistemic space. Curiosity and creativity might thus share principles for reaching intrinsic epistemic goal states. Our proposal is aligned with work on artificial curiosity and creativity, which have had to make careful distinctions between intrinsic and extrinsic motivations and carefully refine concepts like novelty. In particular, this work shows that standard conceptualizations of novelty and surprise are deeply problematic (e.g., Oudeyer, 2018; Schmiedhuber, 2010).

Curiosity and creativity as expressions of a common epistemic drive

Curiosity might share computational principles with creativity insofar as both invoke active sampling for reaching epistemic goal states. The states of interest in an epistemic drive are how well ideas and facts are interrelated, and how much freedom remains to move between ideas, solution, and understandings following acquisition of new information. The aim of the epistemic drive may thus be construed as to maximize information connectedness across perspectives. For curiosity this entails seeking information to arrive at a knowledge state congruent with experience, for creativity it entails testing information combinations until a valid goal state is satisfied. Importantly, new information may work as effectively against expanded knowledge by entrenching constraints as offering new perspectives that release the constraints and offer new knowledge. This narrows what kind of information is desired for the epistemic drive and suggests a "house-keeping" principle for information seeking. Moreover, an epistemic drive may be adaptive and promote survival in the long term because it promotes behavioral flexibility in the eye of environmental change. Finally, it seems we need to broadly invoke an epistemic drive to account for the behavior of animals or how else can we account for Stoffel's ingenious escapes?

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Getting curiouser and curiouser about creativity: The search for a nuanced model

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Abstract

Ivancovsky et al. propose a novelty-seeking model linking curiosity to creativity. This commentary suggests integrating their work with a stage-based creativity model for additional insights. It also encourages readers to address knowledge gaps identified by the authors, including factors that trigger the pursuit of creative solutions. We aim to refine theory and direct future research to clarify the complex curiosity–creativity relationship.

We read the paper by Ivancovsky et al. on the interplay between curiosity, creativity, and novelty seeking with great interest. The authors' efforts to synthesize these complex constructs into a cohesive, biologically informed framework are both ambitious and praiseworthy. Intuition suggests curiosity and creativity are linked (Loewenstein, 1994) and scholars have written about and examined their interconnection in the past (Csikszentmihalyi, 2014; Hardy, Ness, & Mecca, 2017; Kaufman & Gregoire, 2016). However, few attempts have been made to integrate these constructs into a single, coherent theory (Litman, 2005). Ivancovsky et al. advance the discourse by proposing that curiosity and creativity share a complementary and dynamic relationship that contributes significantly to human innovation. Their novelty-seeking model (NSM) opens new avenues for further scholarly inquiry into this complex but important topic.

Here, we suggest four ways to extend their contribution: (1) Situate the NSM within a stage-based process model of creativity; (2) dive deeper into how different forms of curiosity and creativity are related; (3) further explore conditions that trigger the search for creative solutions; and (4) account for empirical evidence that curiosity and creativity are only weakly related.

Elucidating the complex interplay between curiosity and creativity is a main contribution of the paper. The authors point out a key benefit of curiosity is that it equips individuals with a vast and varied knowledge base, alongside robust general problem-solving skills. These advantages are developed through repeated practice and are often established long before a person faces any particular creative challenge. But curiosity not only fosters a useful knowledge base and the development of general skills, it also enhances an individual's ability to notice when unconventional solutions are needed and can initiate the search for solutions (creative or otherwise). That is, the authors' work strongly suggests curiosity influences creativity through multiple channels, some more studied than others: Curiosity lays the groundwork for creative thinking with the acquisition of knowledge and skills (Anderson, Dixson, Monroy, & Keltner, 2020); it impacts whether an individual will seek out a problem and how they frame it (Harrison, Sluss, & Ashforth, 2011); it predicts the ability to generate innovative solutions (Dailey & Mumford, 2006; Hardy et al., 2017); it affects how deeply individuals engage with problems and how solutions are evaluated (Lonergan, Scott, & Mumford, 2004; Mueller, Melwani, & Goncalo, 2012); it impacts when and how one seeks feedback on creative ideas (Harrison & Dossinger, 2017) and how one handles rejection (Kawamoto, Ura, & Hiraki, 2017); and it predicts persistence on challenging tasks (Lauriola et al., 2015). *Given the many pathways by which curiosity impacts creativity, integrating the NSM and a stage-based process model* (Hardy et al., 2017; Lubart, 2001; Mumford, Mobley, Reiter-Palmon, Uhlman, & Doares, 1991) *might offer a comprehensive approach to predicting who naturally excels in creative endeavors, under what conditions, and how to cultivate creativity more broadly*.

Another way to extend Ivancovsky et al.'s work is to *dive deeper into how various forms of curiosity and creativity are related*. *Depth-curiosity* – also known as epistemic or deprivation curiosity – is the drive to gain a deeper understanding of a subject. It's a compulsion to acquire additional information to reduce uncertainty and alleviate frustration. Conversely, *breadth-curiosity* – also referred to as interest or diversive curiosity – is the drive to seek diverse stimuli simply because the exploration itself is stimulating or pleasurable (Berlyne, 1960, 1966; Harrison et al., 2011; Litman & Silvia, 2006). These forms of curiosity are evident across cultures (Karandikar, Kapoor, & Litman, 2021) and life stages (Piotrowski, Litman, & Valkenburg, 2014), and contribute to the creative process at distinct stages and in unique ways. For instance, depth curiosity may lead to the development of expertise and enhanced problem-solving skills (Harrison et al., 2011; Lydon-Staley, Zhou, Blevins, Zurn, & Bassett, 2021; Zhou, Xiao, & Zhang, 2020), both of which are known to benefit the creative process (Scott, Leritz, & Mumford, 2004). Likewise, because breadth-curiosity is associated with broad information gathering, it is more critical to amassing the wide array of information and experiences that can be instrumental in making remote associations. Integrating a clearer distinction between these curiosity types into a theoretical model could clarify their unique contributions to creativity, help resolve conflicting findings in the literature, and guide future thinking as researchers further articulate the brain networks that subserve this dynamic. Addressing these nuances could also enhance the predictive power of curiosity in creative problem solving by providing a clearer framework for when and why each form of curiosity is beneficial.

Another noteworthy aspect of the paper is its preliminary exploration of the factors that encourage individuals to seek innovative solutions or, alternatively, that make such pursuits seem daunting or unnecessary. Research into what compels an individual to pursue a novel approach to a problem rather than default to a tried and tested solution is scant. Scholarly efforts have largely focused on identifying the traits of highly creative individuals (Amabile, 1996; Feist, 2019; Kandler et al., 2016); we understand comparatively little about the circumstances that prompt an individual, whether typically creative or not, to innovate rather than settle for a standard or routinized approach. The paper's efforts to *identify the conditions under which people self-initiate creative pursuits* highlight areas ripe for further research.

Finally, the paper raises an intriguing paradox: *If curiosity and creativity are deeply intertwined, why do empirical studies observe only modest correlations between the two?* Correlations in past research are less straightforward than theory would suppose. For example, the recent meta-analysis (Schutte & Malouff, 2020) cited by the authors found curiosity and creativity to only be weakly related once self-report measures of creativity were discounted (e.g., $r = 0.16$). Furthermore, a frequent refrain in curiosity research is that not all forms of curiosity contribute to creativity equally (Hardy et al., 2017; Harrison et al., 2011; Koutstaal, Kedrick, & Gonzalez-Brito, 2022; Whitecross & Smithson, 2023). These findings imply a complex interplay deserving of closer scrutiny. Which types of curiosity are more essential to creativity, at which stage in the process, and under what conditions? This puzzle reinforces the need for a nuanced, stage-based model to delineate the various curiosity–creativity interactions and provide a structured approach for future research in this domain.

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Curious? The relationship between curiosity and creativity is likely NOT novelty

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Abstract

The target article tackles an important and complicated issue of the underlying links between curiosity and creativity. Although thought-provoking, the target article overlooks contemporary theories and research on these constructs. Consequently, the proposed model is inconsistent with prior research in the developmental and educational fields and would benefit from better specification and clarity around key constructs and processes.

The target article presents a heroic review of the literature on curiosity and creativity. For decades, scholars have suspected that the two constructs are related to recent research sparking renewed interest. Yet, the curiosity and creativity research landscape is dotted with nuanced terms like open-ended versus goal directed, divergent versus convergent thinking, exploration versus exploitation, and originality versus usefulness, to name a few. Ivancovsky et al. suggest that these terms can be aligned under a unified theory – novelty seeking – and claim to be among the first to establish a link between curiosity and creativity. Yet, prior research in other fields *does* establish this link. Thus, although we applaud the target article for tackling this complicated issue and acknowledge its important contributions, we worry about some of the claims made and issues related to missing broader literature.

Signaling out *novelty seeking* as the mechanism that links creativity and curiosity is not supported by numerous conceptual, theoretical, and empirical studies from research in developmental and educational fields. Several researchers studied curiosity and creativity in authentic educational contexts (Scott-Barrett, Johnston, Denton-Calabrese, McGrane, & Hopfenbeck, 2023) and explored links between survey and direct measures of curiosity and creativity (e.g., Evans & Jirout, 2023; Schutte & Malouff, 2020). Other theories presented alternative views linking curiosity and creativity based on *uncertainty* rather than novelty (i.e., Evans, Todaro, Golinkoff, & Hirsh-Pasek, 2022; Jirout & Matthews, 2022). The focus on novelty in the novelty-seeking model (NSM) as an umbrella term to include theoretically distinct constructs is problematic. This is best demonstrated in the text: "…novelty appraisal (including incongruity, complexity, unexpectedness, obscurity, and uncertainty; …)" (target article, sect. 2.5, para. 5) where novelty is used as a catch-all, rather than its traditional meaning of *new*, *original*, or *unfamiliar*.

Studies demonstrate important differences between novelty and uncertainty or ambiguity, terms that could suggest moderate levels of novelty on a continuum, but the target article discusses novelty as noncontinuous. For example, in Loewenstein's curiosity research, participants rate curiosity highest in a state of uncertainty (tip-of-tongue) compared to novelty (unfamiliar/unknown), and this is replicated with behavioral measures in adults (Litman, Hutchins, & Russon, 2005) and children (Schulz & Bonawitz, 2007). This work builds on a long history of considering novelty as continuous or distinct from these related constructs (e.g., Kreitler, Zigler, & Kreitler, 1975; McReynolds, Acker, & Pietila, 1961). Creativity research similarly specifies the importance of uncertainty in definitions (Beghetto, 2021), such as arguing that uncertainty is a prerequisite for novelty (Runco, 2022). Although possible to consider uncertainty as an intermediate level of novelty, the construct of uncertainty might prove a better underlying basis for curiosity and creativity.

The underspecification of definitions and alternating between conceptualizations of the key constructs leads to inconsistencies that could benefit from a more comprehensive look at theories of curiosity and creativity. Berlyne's cited "classical definition" for curiosity didn't include novelty as a core feature. Rather, it suggested that novelty is a trigger for curiosity specifically in the context of an optimal level of novelty and often as it relates to factors like unpredictability or incongruity (e.g., Berlyne, 1966). Later work discusses novelty as more of a general motivator without mentioning curiosity (e.g., Berlyne, 1970). Similarly, a single definition of creativity is given without discussion of other perspectives, and although aspects of the definition include ideas that are both *novel and useful*, all subsequent discussion focuses primarily on divergent and convergent thinking as specific processes that can either be considered creativity on their own or together. How one operationally defines the constructs of curiosity and creativity plays a key role in how one uncovers underlying mechanisms. By way of example, uncertainty and knowledge seeking is a core feature of curiosity and, perhaps, divergent thinking. Yet, uncertainty and novelty might not arise from convergent thinking or the homing in on a solution to a problem.

More clarity is also needed when discussing the difference in how processes like exploration and exploitation align with curiosity and creativity. Is information gained from exploration then exploited? Is exploration just curiosity (intrinsically motivated information seeking) while exploitation drives information toward a creative solution to a problem? The same issues arise in the discussion of curiosity as consisting of two types: feelings of *general interest* (labeled diverse curiosity) and feelings of *deprivation* (labeled specific curiosity). Perhaps, but this articulation conflicts with recent work that separates general interest from curiosity (see special issue on this in *Educational Psychology Review*; Peterson & Hidi, 2019), and work showing interest-driven curiosity (different from general interest) and deprivation curiosity are related but distinct (Piotrowski, Litman, & Valkenburg, 2014; Ryakhovskaya, Jach, & Smillie, 2022), with only interest curiosity relating to developing an accurate knowledge base through information seeking, whereas deprivation curiosity related to susceptibility to misinformation and errors, and lower knowledge base and intellectual humility (Zedelius, Gross, & Schooler, 2022). See also the long and robust line of research on epistemic emotions that include important considerations about curiosity (e.g., Pekrun, 2019; Vogl, Pekrun, Murayama, & Loderer, 2020). Figure 2 of the target article attempts to add clarity, but sadly leaves the uncertainty about the relationships between these many constructs unclear. An explanation of the distinctions between each of the types of curiosity and creativity discussed is needed, specifically how diversive curiosity differs from divergent thinking and specific curiosity differs from convergent thinking. This muddying of distinctions between constructs is problematic for uncovering underlying mechanisms.

We appreciate the important discussion and the consolidation of research that illuminates the connection between curiosity and creativity in the target article. The general model of moving from broader information seeking to a convergence on a good solution is important to consider in future research. As argued, there are clearly shared processes between curiosity and creativity. Whether novelty seeking is the missing link is less clear. A broader review of the literature that includes work in developmental and educational psychology and better operational definitions of key terms – including clear demarcations of terms like curiosity and the divergent thinking arm of creativity – may suggest otherwise. Although this is not the first article to link these important constructs, it is an important thesis that deserves serious consideration.

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Be curious: Strategic curiosity drives creativity

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Abstract

Ivancovsky et al. provide a compelling argument for the role of curiosity in creative thinking. We argue that (a) trait-like curiosity is necessary to engage in creative actions and (b) state-like curiosity might be effectively and strategically induced during interventions. Thus, we posit that curiosity works in an agentic and strategic way in strengthening creativity.

One of the greatest minds of all time – Albert Einstein – credited passionate curiosity rather than special talents for his scientific discoveries. While we doubt that curiosity alone would ever suffice to make contributions Einstein made, considering curiosity a powerful driver of creativity goes without saying. Therefore, Ivancovsky et al.'s review (target article) is ambitious and timely. In this commentary, we offer some additional routes for considering the links between curiosity and creativity, specifically by emphasizing the role of curiosity in creative activity rather than creative thinking.

Curiosity and creativity are broad constructs that surprisingly rarely intersected so far (but see Gross, Zedelius, & Schooler, 2020). Curiosity is multidimensional – to mention exploratory and deprivation curiosity – and so is creativity. In their feature article, Ivancovsky et al. focus exclusively on creative thinking, but real-life creativity requires action: Taking unknown and risky routes. A feeling of agency drives such action. When people hold confidence (i.e., feel that they possess the necessary skills to deal with tasks and problems) and consider being creative central to their identity, the chances for engaging in creative activity grow (Karwowski & Beghetto, 2019). Consequently, we posit that curiosity, mainly exploratory curiosity, plays a vital role in creative agency. Moreover, we see curiosity as an effective strategy for stimulating people's creative engagement. Below, we unpack this reasoning, hoping to enrich Ivancovsky et al.'s perspectives.

As a recent meta-analysis (Schutte & Malouff, 2020) demonstrated, there are robust links between trait-like curiosity and self-reported creativity ($r = 0.52$), but a negligible correlation when rated creativity is considered ($r = 0.16$). Another study (Karwowski, 2012) found a strong latent correlation ($r = 0.72$) between exploratory curiosity (stretching) and creative self-efficacy and only slightly weaker links between creative self-efficacy and embracing (i.e., accepting unpredictability, $r = 0.67$). At the same time, there are robust links between creative confidence and openness to experience (Karwowski & Lebuda, 2016), and curiosity occupies a prominent place in the structure of openness (Christensen, Cotter, & Silvia, 2019), so openness might confound the relationship between curiosity and creative agency. In short, however, although studies relying on trait-like self-report measures do not allow for causal conclusions regarding the links between curiosity and creative agency, creative activity and – consequently – creative accomplishments seem unlikely without exploratory curiosity. Not only are creative writers characterized by a higher level of curious daydreams than non-writers (Zedelius & Schooler, 2021), but there are also synergetic effects of creative confidence and intellectual risk-taking (a factor closely conceptually related to exploratory curiosity) in explaining creative activity and achievement across various domains (Beghetto, Karwowski, & Reiter-Palmon, 2021).

Apart from the role of trait-like curiosity in creative action, studies utilizing micro-longitudinal, dynamic designs show that a large amount of variability in both curiosity (Kashdan *et al.*, 2013; Lydon-Staley, Zurn, & Bassett, 2020) and creative behavior (Karwowski, Lebuda, Szumski, & Firkowska-Mankiewicz, 2017; Silvia *et al.*, 2014; Smith, Pickering, & Bhattacharya, 2022) stems from within- rather than between-person variation. Regardless of people's relatively stable tendencies to engage in novelty-seeking behavior, the state of being curious and the engagement in creative activities vary on a daily or even moment-to-moment basis.

Thus, the link between curiosity and creativity is likely reciprocal (see Ma and Wei, 2023). The state of curiosity, particularly its approach-oriented nature, holds the potential to motivate and support actual action. As proposed elsewhere (Kashdan & Fincham, 2002), state-like curiosity might serve as a self-regulatory mechanism promoting creative engagement and sustained efforts toward creative goal attainment. However, empirical attempts to test such boosting effects of state curiosity are scarce. Apart from experimental designs, we see great potential for examining the curiosity–creativity dynamic link in research that uses experience sampling methodologies. For instance, the state of curiosity predicts next-day creativity among semi-professional creators (Hagtvedt, Dossinger, Harrison, & Huang, 2019, Study 2). The mechanism where state-like curiosity drives creative engagement has apparent practical implications. Is it possible to make people more willing to engage in creative actions by enhancing their feelings of curiosity?

We propose that curiosity might be strategically induced during wise interventions (Walton & Crum, 2021), thus building engagement in real-life creative activities. Such interventions promote or change specific behaviors by providing opportunities to develop a new way of thinking about the self or look at a situation differently. Given the central role of evaluations or appraisals in conceptualizations of curiosity (e.g., Pekrun, 2019; Silvia, 2008), altering what and why people feel curious can effectively and strategically stimulate their creative engagement.

Take, for example, a daily diary intervention (Zielińska, Lebuda, & Karwowski, 2022), which showed that boosting people's creative confidence and making the importance of creativity more salient results in greater engagement in everyday creative activities. These effects were achieved using brief prompts that – although focused on strengthening creative agency – also sparked curiosity. For instance, one of the tasks read: *Over the course of today and tomorrow, try to reflect and generate some sensible reasons for being creative. What does this give us? What does it mean for yourself and other people? Whether – and why! – is it worth developing your own and other people's creativity? Try to ask yourself these questions in different situations.* Such prompts, while fostering creative centrality and confidence, increased the intrinsic value of creative functioning and its usefulness (Dubey, Griffiths, & Lombrozo, 2022) and promoted curiosity. Moreover, they resulted in a higher likelihood of creative activity the next day. We believe these kinds of interventions form a valuable addition to experimental studies, particularly those employing behavioral measures of curiosity (Gross *et al.*, 2020), and offer a deeper understanding of the dynamic interplay between creativity and curiosity in real-life contexts.

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The costs of curiosity and creativity: Minimizing the downsides while maximizing the upsides

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Abstract

The unbridled positivity toward curiosity and creativity may be excessive. Both aid species survival through exploration and advancement. These beneficial effects are well documented. What remains is to understand their optimal levels and contexts for maximal achievement, health, and well-being. Every beneficial element to individuals and groups carries the potential for harm – curiosity and creativity included.

Curiosity and creativity are (rightfully) defined as psychological strengths or positive goods (e.g., Peterson & Seligman, 2004). From an evolutionary perspective, both aid species survival. Curiosity ensures that an agent explores anything that is new, uncertain, complex, or ambiguous in the environment. By doing so, there is opportunity to capitalize on rewards such as the medicinal value of plants or attaining status. An agent is also attuned to perturbations in the self (inward directed) or environment (outward directed) that could suggest potential insult, injury, or premature death. As for creativity, agents that design new and useful contributions are more likely to be valuable and thus, accepted and protected. At a societal level, creativity drives economies, underlies paradigm-shifting inventions, and offers solutions to global crises (Florida, 2014).

From a psychological angle, there is evidence that people exhibiting greater curiosity and creativity benefit in terms of greater achievement, health, and well-being (in particular, vitality, meaning and purpose in life, psychological healing, and satisfying needs for autonomy and competence) (e.g., Acar, Tadik, Myers, Van der Sman, & Uysal, 2021; Kaufman, 2023; Silvia & Kashdan, 2009). Curious and creative people are more likely to be successful entrepreneurs with larger social and professional networks. Conditioning on the beneficial consequences fits with a larger theme that there is a "shared novelty-seeking basis for creativity and curiosity" (Ivancovsky, Baror, & Bar, this issue) that buffers against threats to a better life (cf. hedonic adaptation; Sheldon & Lyubomirsky, 2007).

As with many psychological strengths, there are predictable, replicable situations with unintended costs (Biswas-Diener, Kashdan, & Minhas, 2011; Grant & Schwartz, 2011). Unintended costs are inevitable with competing demands for our time and attention. There are metabolic costs, as the brain consumes energy to process new information. There are social costs, as those constantly seeking novelty may be seen as eccentric or disruptive. And there are psychological costs, as the constant pursuit of novelty can be mentally exhausting.

Is too much of a good thing, a good thing?

Curiosity is characterized as the enjoyable pursuit of new knowledge. However, curiosity comes in more than one flavor. Unlike the Joyous Exploration dimension of curiosity (i.e., Kashdan, Disabato, Goodman, & McKnight, 2020), there is Deprivation Sensitivity or the uncomfortable urge to fill an information gap (Litman, 2005). Both have metabolic costs that arise from orienting attention to the new, detecting information gaps, and making sense of the target of curiosity (Gruber & Ranganath, 2019).

Deprivation Sensitivity has additional burdens. There is a restless need to know and a sense of frustration, triggered by a lack of information (Schweitzer, Gerpott, Rivkin, & Stollberger, 2023). To the outsider, an agent experiencing deprivation sensitivity appears to be anxious and neurotic – definitely not in the throes of well-being.

Strangers, close friends, and family possess mixed reactions to highly curious individuals. Highly curious people are perceived as having a high intellectual capacity and being imaginative, humorous, and non-judgmental; on the flip side, they are viewed as somewhat critical, rebellious, and distant (going into interviewer mode) (Kashdan, Sherman, Yarbro, & Funder, 2013).

Similarly, creativity is explicitly praised, but bosses may show implicit bias against creative workers (Mueller, Goncalo, & Kamdar, 2011), possibly because it can be associated with lower company loyalty (Madjar, Greenberg, & Chen, 2011) and quality (Miron, Erez, & Naveh, 2004). Teachers, too, show a comparable split between explicit and implicit views (Westby & Dawson, 1995). Creativity is often assumed to result in benevolent outcomes. However, creativity is not bound to any morality. Creativity can be used for negative ends which benefit the creator at the expense of others (such as stealing from work) or downright malevolent acts, with the goal being to cause harm (Kapoor & Kaufman, 2022).

Creativity is often linked to mental illness, although these connections are often exaggerated or overly generalized. However, Carson (2014) suggests that neurocognitive factors can be "shared vulnerabilities." Neural hyperconnectivity (i.e., uncommon areas of the brain being connected, as in synesthesia), lower latent cognitive disinhibition, and a need for novelty can help someone be more creative – or more likely to develop psychopathology. Further, the creative process can trigger specific anxiety that is distinct from general anxiety (Daker, Cortes, Lyons, & Green, 2020).

Creative people have been likened to investors, choosing to put their time and resources toward a particular project (Sternberg & Lubart, 1995). Successful creators will buy low (unpopular) ideas, convince others of their value, and then sell high and move on to their next idea. A creator's decision to pursue any particular idea means they have less time to follow a different idea.

Optimal levels

Insufficient consideration is given to an inconvenient truth: there are always psychological trade-offs when investing in a behavior. In this case, we consider predictable ways that being curious and creative are costly. Think of finite resources – attention, time, money, and energy – that can be spent on other, more beneficial life pursuits that create a more well-rounded person. Some of the most powerful interventions for a good life such as exercise, diet, being in the company of pets, or spending time outside on a sunny day are often mundane habits.

Opportunity costs aside, there are social consequences that may lead to negative evaluations and/or social isolation (e.g., Mueller & Yin, 2021). The highly curious and creative often hold different ideas and perspectives than others. These differences lead to discriminatory actions by others and significant financial (e.g., rejection of novel ideas), personal (e.g., low self-worth), and interpersonal costs (social group rejection). Furthermore, at times, curiosity and creativity at their maximum produce overstimulation due to the vigilance demands and as a result, emotional well-being declines.

Despite a voluminous literature on curiosity and creativity, we know little about optimal levels of curiosity and/or creativity. We need to uncover when there is too much, when they are wrongly applied, and when costs outweigh benefits to the point of dysfunction. Determining optimal levels is the province of wisdom, metacognition, morality, and work–life balance, among other factors. We hope a conversation on trade-offs catalyzes research on what works best for whom in particular situations.

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Breaking down (and moving beyond) novelty as a trigger of curiosity

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Abstract

The Novelty Seeking Model (NSM) places "novelty" at center stage in characterizing the mechanisms behind curiosity. We argue that the NSM's conception of novelty is too broad, obscuring distinct constructs. More critically, the NSM underemphasizes triggers of curiosity that better unify these constructs and that have received stronger empirical support: those that signal the potential for useful learning.

Ivancovsky et al. propose a "Novelty Seeking Model" (NSM) of curiosity and creativity, grounded in the idea that both share common novelty-seeking mechanisms – directed toward novel stimuli, for curiosity, and novel ideas, for creativity. In the *evaluation* step of the NSM as applied to curiosity, stimuli are evaluated for their novelty (among other considerations), and this determines whether a person becomes curious. Here, we raise two challenges for this step. First, the NSM blurs the lines between several distinct constructs, labeling them all "novelty." Second, novelty is emphasized at the expense of other relevant evaluations, including those with stronger empirical support. We discuss each of these in turn.

Ivancovsky et al. refer to several constructs under the umbrella term "novelty," arguing that this broad grouping is a key part of the evaluation step. For example, they write that curiosity is determined by a "novelty appraisal (including incongruity, complexity, unexpectedness, obscurity, and uncertainty…)" (sect. 2.5, para. 5). This grouping is puzzling, as these constructs are definitionally distinct (Barto, Mirolli, & Baldassarre, 2013; Liquin, Callaway, & Lombrozo, 2020). For example, novelty describes a lack of prior experience or exposure, unexpectedness describes a violation of one's predictions, and uncertainty describes a lack of knowledge.

Further, each construct makes different predictions about curiosity. Imagine that you notice a new flag outside your neighbor's home. The flag is novel to you (you've never seen it before), and you are uncertain about its meaning (is it some country's flag?). You're curious, but you forget to look it up. The next day, you see the flag again. It is no longer novel (you saw it yesterday), but you remain uncertain. If novelty alone drives curiosity, then curiosity should be lower on the second day than on the first. But if uncertainty alone drives curiosity, then curiosity should remain the same. Similar reasoning can be used to tease apart the concepts of novelty and *surprise* (Barto et al., 2013), which is often seen as synonymous with unexpectedness (but see Maguire, Maguire, & Keane, 2011).

By blurring the lines between these constructs, Ivancovsky et al. obscure important questions about curiosity's occurrence. For instance, is curiosity responsive to a combination of these cues (sometimes novelty, sometimes uncertainty, sometimes surprise or unexpectedness, sometimes all three)? Or is there some other construct that unifies and explains the associations between curiosity and each cue?

We have argued elsewhere that curiosity might be sensitive to novelty, surprise, and related evaluations precisely because these cues signal *the likelihood of future learning* (Liquin et al., 2020, 2021; Liquin & Lombrozo, 2020). Supporting this claim, curiosity is highest when expected learning is highest, above and beyond variation in novelty, surprise, or uncertainty (Liquin & Lombrozo, 2020; see also Lombrozo & Liquin, 2023). Related work shows that the association between uncertainty and curiosity is modulated by future utility. People aren't curious about *all* uncertain stimuli, but specifically those likely to be useful in the future (Dubey, Griffiths, & Lombrozo, 2022; Dubey & Griffiths, 2020). Moreover, curiosity is correlated with moment-to-moment variation in learning progress: the rate at which one's predictions are improving (Poli, Serino, Mars, & Hunnius, 2020, 2022; Ten, Kaushik, Oudeyer, & Gottlieb, 2021).

This growing body of research suggests that curiosity goes beyond novelty and related cues. Curiosity is triggered by expected learning, learning progress, and utility – even controlling for variation in novelty, surprise, and uncertainty. Moreover, expected learning, learning progress, and utility tend to dominate when predicting variation in curiosity.

Ivancovsky et al. acknowledge that curiosity may depend on additional appraisals beyond novelty: (1) whether it is possible to understand the curiosity-inducing stimulus ("coping potential") and (2) how useful it would be to understand the curiosity-inducing stimulus. It is not clear how the former appraisal is integrated into the NSM. For the latter, Ivancovsky et al. propose that the relative weight given to novelty versus utility is determined by one's state of mind and level of inhibition. However, under the NSM, coping potential and utility are always subsidiary to novelty, as novelty is also what initially attracts attention to a stimulus (in the affinity step of the NSM). Indeed, Ivancovsky et al. define curiosity as a "state by which one seeks novelty," thus presupposing that novelty is primary.

Instead, we argue that *expected learning* and *utility* are primary, as they describe the function of curiosity for human cognition – to motivate us to learn useful information. Curiosity is sensitive to cues like novelty because these cues signal, sometimes imperfectly, that useful learning is likely. But more direct signals (e.g., expected learning, learning progress, utility) are stronger triggers of curiosity. This makes sense, as sensitivity to these triggers is likely to produce "optimal" patterns of curiosity: high curiosity when useful learning is most likely and most rapid, and low curiosity when useful learning is least likely and least rapid (Liquin et al., 2020, 2021; Poli et al., 2020).

Ivancovsky et al.'s key claim is that curiosity and creativity are unified by virtue of their novelty-seeking mechanisms. If curiosity is not geared toward novelty but rather toward useful learning, can curiosity and creativity be unified after all? One path forward is to consider the functional role that *creativity* plays in supporting human cognition, just as we have considered the functional role of curiosity. Perhaps at this functional level, we will find new ways of approaching a unified account of curiosity and creativity.

This functional approach also invites us to consider how the mechanisms underlying creativity support its functional role. In the case of curiosity, a functional focus has led to important insights concerning the triggers of curiosity: that novelty, surprise, and uncertainty can be unified by their connection to future useful learning, and that people's curiosity is most strongly predicted by their expectations about future useful learning. Similarly, we might ask why creativity depends on assessments of novelty and usefulness – how do these assessments support creativity's function? Ultimately, answering questions inspired by a functional approach will provide a richer understanding of both curiosity and creativity – and, perhaps, a unified model.

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Curiosity is more than novelty seeking

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Abstract

The novelty-seeking model (NSM) does not offer a compelling unifying framework for understanding creativity and curiosity. It fails to explain important manifestations and features of curiosity. Moreover, the arguments offered to support a curiosity–creativity link – a shared association with a common core process and various superficial associations between them – are neither convincing nor do they yield useful predictions.

Ivancovsky et al. make an ambitious attempt to link creativity and curiosity, two complex cognitive constructs, via a shared novelty-seeking process. Although intriguing, the novelty-seeking model (NSM) they propose to support this creativity–curiosity link is problematic in ways that undermine the value of their contribution. A good model should account for existing features of the constructs it tries to explain, and make precise predictions that allow it to be evaluated, both on its own and against alternative theories. Yet the NSM is unable to account for fundamental features of curiosity and fails to make clear predictions that allow for comparisons with existing curiosity theories.

The NSM posits that information is attended to in accordance with its novelty and value, but this fails to explain why people attend to new information with no obvious value and, conversely, ignore valuable novel information. In particular, people regularly invest resources to acquire information with no instrumental value, purely to satisfy their curiosity. Examples include: celebrity gossip, self-categorization questionnaires (e.g., "which Harry Potter character are you?"), and useless trivia. Psychologists have long recognized that people are indeed curious to learn such seemingly useless information, and economists have also recently documented a demand for information with no obvious utility (Eliaz & Schotter, 2010). It is not clear, within the NSM, why there would be any attraction and thus attention to such information (affinity phase), or why it would cross the threshold for saliency (activation phase). Even more problematically for the model, why would such noninstrumental information be considered relevant and judged to hold merit despite not being useful (evaluation phase)? These are interesting and important questions, the answers to which are likely to shed light on the kinds of information the brain prioritizes and why. The NSM also fails to explain why many novel stimuli in our environment are ignored, despite actually being valuable. For instance, people often fail to notice changes in their spending patterns or calorie information on restaurant menus. A full account of curiosity needs to explain why relevant pieces of information regularly fail to capture our curiosity while many trivial pieces of information do so far too easily. The NSM does not offer satisfactory explanations.

In contrast to the NSM, some other theories of curiosity do provide concrete predictions about what triggers or reduces curiosity. For example, Wojtowicz and Loewenstein (2020) argue that curiosity results from a need to efficiently allocate attention, whereas the information gap theory (Golman & Loewenstein, 2018; Loewenstein, 1994) posits that curiosity is triggered by a need to address an aversive feeling resulting from an exposed, salient gap in our knowledge combined with an apparent availability of the missing information. As such, these alternative theories make testable predictions concerning when curiosity will be piqued (or not). An important feature of these other theories is their focus on specific curiosity (a feeling of deprivation of information) rather than diversive curiosity (a motive to explore one's environment) (Berlyne, 1966).

Ivancovsky et al. attempt to account for both types of curiosity but often fail to distinguish between them, and sometimes erroneously overgeneralize findings that only hold for one type of curiosity as being applicable to curiosity in general. For example, contrary to what they suggest, curiosity is not always associated with risk tolerance. Although diversive curiosity may be associated with higher risk tolerance, specific curiosity is often associated with lower risk tolerance (Whitecross & Smithson, 2023), much like other forms of deprivation (Liu, Tsai, Wang, & Zhu, 2010; Rad, 2023; Shiv, Loewenstein, Bechara, Damasio, & Damasio, 2005). In fact, the relationship between curiosity and preference for (vs. aversion to) uncertainty is likely even more complicated and nuanced. For example, our own research shows that, when piquing specific curiosity, people tend to be more risk averse in their demand for noninstrumental information when it comes to acquiring it, but more risk seeking when facing the prospect of losing (the possibility of learning) it (Litovsky, Loewenstein, Horn, & Olivola, 2022). Although Ivancovsky et al. do cite recent research suggesting that specific curiosity is less relevant for creativity than diversive curiosity (Schutte & Malouff, 2020), they do so in passing, and otherwise largely ignore this critical distinction.

We also see problems in the way Ivancovsky et al. attempt to link curiosity to creativity. The mere fact that both are related to novelty seeking does not constitute compelling evidence of a meaningful connection. Novelty is a basic psychological need (González-Cutre, Sicilia, Sierra, Ferriz, & Hagger, 2016) and novelty seeking an adaptive (Brockmole & Henderson, 2005; Wittmann, Daw, Seymour, & Dolan, 2008) and rewarding behavior (Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006), associated with a range of other behaviors, including sensation seeking (McCourt, Gurrera, & Cutter, 1993) and variety seeking (McAlister, 1982). Two states or behaviors being related to a given need is a poor indicator of a relationship between them, given that many unrelated states and behaviors reflect the same basic physiological or psychological needs. Similarly, the fact that curiosity and creativity both trigger reward-related neural changes in the brain is not sufficient evidence of a relationship between them, given that the brain's reward circuitry underlies myriad human behaviors, from drug use (Bardo, Donohew, & Harrington, 1996) to charitable giving (Spaans, Peters, & Crone, 2019).

In sum, Ivancovsky et al.'s proposed NSM theory fails to explain commonly observed manifestations of curiosity. Moreover, most of the arguments they present to support the curiosity–creativity link – a shared association with a core process and very broad, superficial correlations between them – are neither highly compelling nor particularly useful for generating valuable predictions. As a result, although ambitious in its scope, the novelty-seeking basis for creativity and curiosity neither substantially furthers our understanding of curiosity nor offers a valuable alternative to existing theories.

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Exploratory exploitation and exploitative exploration: The phenomenology of play and the computational dynamics of search

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Abstract

I argue for a more complicated but nonetheless computationally feasible and algorithmically intelligible interplay between exploration and exploitation and for admitting into our conceptual toolkit regimes of *exploitative exploration* and *exploratory exploitation* that can enhance the novelty and usefulness of the results of either problemistic or serendipitous search.

Categorical classifications of patterns of mental behavior can be useful exploratory tools, because, while believing in them, one can take seriously a set of possible worlds or states of the world that one could not otherwise – which makes systematic search within those worlds possible (Aronowitz, 2021). A map of the relationship between curiosity and creativity such as that of Ivancovsky et al. is a case in point: By a somewhat arbitrary fixing of the referents of both "curiosity" and "creativity," one can explore a space of possible relationships that would make less sense otherwise. For instance, we can inquire about the *fine structure* of curiosity and how it can be harnessed for useful work in spite of its "open-ended" nature.

Ivancovsky et al. recognize that cognitive control plays an important role in the dynamics of curiosity (Steele, Hardy, Day, Watts, & Mumford, 2021), minimally as a gatekeeper on what constitutes information that is either useful interesting or useful (Campbell, 1960). But, reducing the exercise of control to both the cognitive realm and to one variable – that one can have more or less of – over-simplifies the "facts of the neuro-phenomenological matter" as far as human search is concerned, just as the representation of the exploration–exploitation relationship as a trade-off that happens on a continuum of different "proportions" does.

For example, one may search for a small object (cell phone) lost in a large region of space–time (1 day × 10 square miles) in many ways:

- some involve the exhaustive coverage of every place within the perimeter, perhaps with a "random" starting point but thereafter determined sequential steps;
- some involve recalling and retracing of one's own remembered steps (which may be a function of one's current mood or location), or calling, "in random order" of public locales in the neighborhoods one has visited, or
- one might call a few "random" friends or acquaintances and attempt to playfully engage them in the search.

One can also *switch* between different approaches during the search, depending on how well "things are going." Even in a search like this one – in which the desired end state is well defined – there are ample opportunities for the exercise of a taste for the unpredictable and the unknown, and the act of randomization can itself supply that in ways that can be productively marshaled to getting to the end goal more reliably and/or quickly.

When the end goal is less well defined or the search space is much larger – or both – the structure and dynamics of the interplay between exploration and exploitation become correspondingly more textured: One may search for the set of features of a new software platform that will deliver the functionality and form one surmises a set of clients would deem preferable to what one currently surmises the competition will come up with, by searching among all of the $2^N - 1$ – many subsets of some large number N of possible features and doing thought experiments and real experiments to figure out how they would, should, or might perform in the possible worlds in which a potentially large number M of clients have beliefs and desires that lead them to choose the product embodying these features over another product made by one or more of K competitors, each currently facing a different predicament. The exhaustive sweep of the entire search space does not seem feasible, but one can weave exploration and exploitation together in many ways to create viable – and even provably "optimal," in best-, worst-, and average-complexity senses – search paths:

- Randomly jump to different subsets of features and evaluate them and subsets that are closely related to them, switching from the existing location in search space to another if the results do not seem promising;
- Start with an "intuitive" set of features, evaluate the current configuration, and then replace a few of them at random with close substitutes; repeat until a marked improvement is seen;
- Start with subassemblies of features and randomly combine them into a full feature set; evaluate and try again, keeping track of increases or decreases in an overall desirability metric, and so on.

To an algorithm designer, these are reasonable adaptations of the search procedure to a large search space – which benefit from the purposeful and disciplined introduction of a stochastic element in the sequence of search operations. To the introspective eye of the individual, these cases feature episodes that may "feel" like the playful prospecting that curious "states of mind" are associated with. Randomization need not entail a call to a pseudorandom number generation routine or the tossing of coins: Environmental or internal "switch triggers," duly interpreted as prompts, can serve as a randomizing device (Moldoveanu & Martin, 2010) – which entails one can engage in "randomized search acts" just by following interesting cues "out of curiosity" or indulging an instinct for "curious exploration." At the same time, she can *explore* the ways in which her own *exploitative* behaviors "work out" as her nerve endings make contact with energy-bearing signals: How do her own motor neurons implement targeted, timely commands that cause environmental effects in a predictable fashion as she is "following a recipe" or algorithm that prescribes them – which may lead her to discover more efficient ways of gripping, handling, turning, or moving an object "the next time around"?

The interplay between the "phenomenology of playful search" and the "computational structure of large scale search" (Moldoveanu, 2024) introduces a new dialectic in discourse about "the interplay of curiosity and creativity" to complement that between cognitive psychology and neuroscience. It affords us new insight into the ways in which regimes of exploratory exploitation and exploitative exploration can help people create useful solutions to large problems through the disciplined use of curious "look-abouts."

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Beyond novelty: Learnability in the interplay between creativity, curiosity and artistic endeavours

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Abstract

Using art and aesthetics as context, we explore the notion that curiosity and creativity emanate from a single novelty-seeking mechanism and outline support for the idea. However, we also highlight the importance of learning progress tracking in exploratory action and advocate for a nuanced understanding that aligns novelty-seeking with learnability. This, we argue, offers a more comprehensive framework of how curiosity and creativity are related.

Producing art is arguably one of the most ubiquitous and universally recognizable expressions of creativity. Similarly, curiosity is believed to play a central role in the aesthetic experience, driven by the novelty, ambiguity and uncertainty that are engendered by many artworks. The novelty-seeking model (NSM) proposed by Ivanconvsky et al. suggests that curiosity and creativity both result from the same mechanism of novelty-seeking, which is, in turn, influenced by one's state of mind. How effective is this model in accounting for the human motivation to produce and appreciate art?

We suggest that the model indeed offers considerable explanatory value in the context of art and aesthetics. For instance, many art forms span a spectrum that ranges from highly structured and representational to highly complex and unpredictable. The presence of the latter category, exemplified in atonal music from the 20th-century Western art-music canon, clearly illustrates how humans sometimes prioritize an exploratory state of mind over an exploitatory one (Mencke, Omigie, Quiroga-Martinez, & Brattico, 2022).

Further, various art forms provide empirical support for the model's proposition of a shared neural basis for creativity and curiosity in the brain's dopaminergic areas (De Aquino, Verdejo-Román, Pérez-García, & Pérez-García, 2019; Omigie *et al.*, 2019; Schuler *et al.*, 2019; Tik *et al.*, 2018). Dopamine medication has been shown to modulate creativity levels in individuals with Parkinson's disease when they engage in the production of visual artwork (Garcia-Ruiz, Martinez Castrillo, & Desojo, 2019; Lhommée, *et al.*, 2014). Concerning curiosity and art appreciation, the modulation of tonic dopamine levels in healthy participants influences the degree to which they like and choose to engage with different styles of paintings and music (Cattaneo *et al.*, 2014; Mas-Herrero, Dagher, & Zatorre, 2017).

However, we have some concerns regarding NSM's ability to be reconciled with other valuable assertions about how curiosity emerges. Notably, learning progress theories, widely applied to artificial agents, posit that curiosity is not solely driven by novelty but is precipitated by heightened rates of learning new information (Oudeyer, Kaplan, & Hafner, 2007). This framework implies that humans are intrinsically driven to pursue tasks featuring a learning-progress component (Ten, Kaushik, Oudeyer, & Gottlieb, 2021), thus influencing both immediate engagement with the task at hand and the selection of subsequent tasks. This dynamic interplay ultimately contributes to an augmented understanding of the evolving environment, achieving desirable reductions in uncertainty (Poli, Meyer, Mars, & Hunnius, 2022).

Learning can be costly and success is never guaranteed. Therefore, having the ability to focus resources on areas where learning is most effective is highly advantageous. Even very young infants seem to possess an innate sense of where they can learn rather than where they might simply encounter random information (Gerken, Balcomb, & Minton, 2011). Curiosity and exploration help us stay in the "zone of proximal development" (Metcalfe, Schwartz, & Eich, 2020; Oudeyer *et al.*, 2007), the optimal range for learning just beyond our current knowledge and abilities. Curiosity, as defined by learning progress theories, limits wasting valuable resources on irrelevant and overly simple content, as well as, importantly, content that is too complex for our current understanding.

Learning progress theories explain how, with continued exposure to complex environments, those stimuli that elicit humans' curiosity, attention and preference will likewise tend to increase in complexity (Forest, Siegelman, & Finn, 2022; Galvan & Omigie, 2022). Learning progress theories thus hold significant potential for explaining our everyday behaviours, including those related to the arts.

Indeed, there is increasing evidence from poetry, visual artworks and music suggesting that learnable novelty is the underlying factor behind curiosity and creative outputs. In the realm of music, research indicates that curiosity, reward and physiological signals are influenced by novelty in ways that depend on the context's learnability (Bianco, Ptasczynski, & Omigie, 2020; Cheung *et al.*, 2019; Omigie & Ricci, 2023). Concerning creativity, it was those musical compositions with moderate, rather than high levels of novel events (i.e., music intervals not previously heard) that were judged by listeners as being the most creative (Zioga, Harrison, Pearce, Bhattacharya, & Di Bernardi Luft, 2020); importantly, the same study also demonstrated that success in learning a new musical style significantly predicted success in composing creatively in that new style.

Such learning–creativity associations align with findings that aesthetic appeal predicts creativity-related judgements and behaviours better than surprise per se (Chaudhuri, Dooley, Johnson, Beaty, & Bhattacharya, 2023; Welke *et al.*, 2023). The experience of aesthetic appeal, which is well explained by individual differences in preference for complexity and novelty, is a stronger predictor than surprise of how creative poems are judged to be (Chaudhuri *et al.*, 2023).

Our artistic sense could be argued to be related to play, another behaviour that is filled with curiosity and exploration. A child will often choose unconventional objects to play with (Andersen, Kiverstein, Miller, & Roepstorff, 2023). This behaviour is not driven by mere novelty-seeking or a desire to signal fitness, as some theories suggest for art (Leder & Nadal, 2014); instead, it is likely rooted in intrinsic motivation to tackle challenging obstacles that, in turn, offer opportunities for learning and progress in understanding the environment. Artists may intentionally incorporate obstacles and challenges into their work. Here, it is relevant to note that curiosity in the form of information-seeking has previously been argued to be a driving factor in both aesthetic experiences and creativity (Kenett,

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Humphries, & Chatterjee, 2023). In doing so, they maintain its appeal, foster curiosity and fresh learning opportunities and benefit both themselves and their audience.

Taken together, we commend the authors for their emphasis on the links between creativity and curiosity and for asserting that distinct states of mind, namely exploratory and exploitative states, underlie different types of creativity and curiosity. Nevertheless, we argue that a more precise qualification of "novelty-seeking" as the pursuit of learnable novel information provides a more comprehensive framework for understanding the similarities between creativity and curiosity. This conceptualization would better align with a growing body of evidence concerning the nature of creativity and curiosity, both in the context of the arts (Gold, Pearce, Mas-Herrero, Dagher, & Zatorre, 2019; Matthews, Stupacher, & Vuust, 2023) and in general (Dubey & Griffiths, 2020). Such a definition would also better accommodate the notion that creative products, including various forms of artistic outputs, serve a recognizable and adaptive purpose.

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Mindfulness, curiosity, and creativity

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Abstract

Curiosity and creativity are manifestations of novelty-seeking mechanisms, closely intertwined and interdependent. This principle aligns seamlessly with the foundational tenets of Langerian mindfulness, which places novelty seeking as a cornerstone. Creativity, curiosity, openness, and flexibility all harmoniously converge in this framework. Spanning over four decades, research in the realm of mindfulness has diligently delved into the intricate interplay among these constructs.

Creativity and curiosity are two of the most important constructs studied in psychology describing human growth, invention, and adaptation (Ivancovsky et al.). It can be argued that closely related constructs also include openness to experience and cognitive flexibility, both particularly associated with psychological well-being and, in general, with the human experience of thriving and flourishing (Dahl, Wilson-Mendenhall, & Davidson, 2020). All these aspects refer to and contribute to explaining the concept of novelty seeking, as persuasively reported by Ivancovsky et al.. This aligns seamlessly with the foundational tenets of mindfulness within the Langerian framework, which places novelty seeking as a cornerstone (Langer, 1989, 2023). Mindfulness can be approached as the reverse of mindlessness, which is what happens when the mind "is not there," being stuck on rigid schemas and relying on automatic pilot. When mindless, people can hardly create anything new, as they are simply reproposing existing patterns; similarly, there is no space for curiosity, as an assumption that supports the application of a rigid schema is the predictability of the context. For similar reasons, mindlessness is incompatible with openness and flexibility. On the contrary, when people are mindful, they are open to novelty with a curious and flexible attitude, paying attention to the variability of the experience. The essence of Langerian mindfulness is attention to variability, a quality of being in the present requiring the understanding that everything, including ourselves, is constantly changing. It is, therefore, incompatible with the mindless idea that a schema can predict or completely describe any situation, whether from the internal or the external world, and it requires the ability to tolerate uncertainty. Being mindful also entails the capacity to adopt multiple perspectives of the current context, facilitating the creation of new categories. In brief, mindfulness is a necessary condition for both curiosity and creativity, and they both contribute to its extent.

Both curiosity and creativity – and the same idea can be extended to openness and flexibility – have already been studied under a common umbrella that defines and extends their potential: the mindfulness framework. Both curiosity and creativity require a reduction in the importance of prior knowledge, focusing on a present that a person actively constructs, by emphasizing the role of the current experience (Pagnini, Barbiani, & Phillips, 2023). Apart from being interrelated from a theoretical standpoint and contributing to the description and operationalization of mindfulness from a sociocognitive perspective (Langer, 1989), the association among these aspects has been extensively studied. Over the course of approximately four decades, research in the realm of mindfulness has diligently explored the intricate interplay among these constructs. For example, the Langer Mindfulness Scale, the most prominent tool for assessing Langerian mindfulness, includes four subscales: Novelty Seeking, Novelty Producing, Flexibility, and Engagement (Pirson, Langer, & Zilcha, 2018). The first two factors directly pertain to curiosity and creativity, respectively. These scales are typically highly correlated with each other (Haigh, Moore, Kashdan, & Fresco, 2011). One recurring finding from studies in this field is that when individuals observe or generate novelty, they acknowledge that actions and beliefs are context-dependent. This awareness can make mindful individuals less susceptible to cognitive biases and less likely to rely on inappropriate heuristics (Maymin & Langer, 2021).

Although the connection among creativity, curiosity, and mindfulness is evident in the Langerian framework, similar outcomes can be observed using a more contemplative approach to mindfulness (Kabat-Zinn, 1994). Specifically, creativity is strongly linked to the ability to observe and mindfully attend to various stimuli (Baas, Nevicka, & Ten Velden, 2014), and curiosity is both stimulated and encouraged by mindful meditation practices, such as inviting a "beginner's mind" (Schattner, 2015).

One curious fact about curiosity itself is the additional distinction introduced from a perspective of Langerian mindfulness: One can be mindlessly or mindfully curious about new things, but one can only be mindfully curious about old things. Questioning mindlessly held assumptions cannot be done while mindless. In this and other respects, the insight that mindfulness is a necessary condition for creativity and knowledge generation can aid in both the design of future experiments and act as a guidepost for day-to-day living. The difference between mindfulness and curiosity is that the latter too often results in mindlessness if once you satisfy your curiosity, you think you know, though you don't know what you don't know – independent of context or perspective.

All the findings obtained within the mindfulness framework not only support the authors' conclusions but also provide a pathway for further expanding their thesis. Although creativity and curiosity have been theoretically and empirically integrated under the mindfulness umbrella, particularly through the concepts of novelty seeking and novelty producing, there are other dimensions of this multifaceted concept yet to be explored. The intricate construct of Langerian mindfulness also encompasses openness and cognitive flexibility, which have been independently examined. An approach similar to the one used by Ivancovsky et al. could extend the current findings, investigating the aspects that interconnect all these concepts, most of which have likely been addressed in decades of mindfulness research.

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Models need mechanisms, but not labels

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Abstract

The target article proposes a model involving the important but not well-investigated topics of curiosity and creativity. The model, however, falls short of providing convincing explanations of the basic mechanisms underlying these phenomena. We outline the importance of mechanistic thinking in dealing with the concepts outlined in this article specifically and within psychology and cognitive neuroscience in general.

Ivancovsky et al. attempt to offer an integrative account of curiosity, creativity, attention, and other aspects of cognitive functioning. We fully appreciate the underlying motive to offer a unified model, but we believe the paper falls short of mechanistically explaining the phenomenon of curiosity and creativity – a problem that is pervasive within psychology and cognitive neurosciences (Hommel, 2020). A good mechanistic theory in cognitive neuroscience would require specifying the basic components underlying a phenomenon and a specification of how these components interact (Bechtel, 2008; Craver, 2006). Instead, what we commonly see is an ever-increasing categorization of new phenomena with circular definitions. An example of this is defining curiosity as a tendency to attend to novel or surprising information and then attributing the tendency to attend to novel or surprising information to curiosity, thereby not shedding any light on what gives rise to this phenomenon.

Such problems are already evident in the description of the role of "attention" in the four-stage novelty-seeking model (NSM) proposed by the authors. The NSM proposes that attention is involved only in the first stage of *Affinity* where "the scope of attention directs the search towards the novel." However, many of the subsequent stages seem to involve mechanisms that sound a lot like attention. For instance, in the *Activation* phase, the authors say that "new combinations potentially cross a relevance threshold, depending on their saliency." Similarly, in the *Evaluation* stage, "involvement of cognitive control is essential for preventing overbursts of stimulation and to efficiently direct the available resources." What specific mechanism warrants invoking the concept of attention in the first stage but not in the others? Viewing attention as a basic selection mechanism would implicate it in all the stages of the NSM model. These issues are further compounded by the fact that "attention" is not at all a unitary concept and a diverse range of behaviour is often attributed to attention (Di Lollo, 2018; Hommel & Colzato, 2015). So, it is not clear which flavour of attention is being discussed in relation to this model. Finally, no one really knows what attention is, how the different forms of attention are similar to or different from each other, and how precisely they differ from other concepts like cognitive control (Anderson, 2011; Hommel et al., 2019).

The lack of mechanistic thinking is also evident in the discussion of the interaction between disinhibition/hyper-inhibition and exploration/exploitation. The concepts of exploration and exploitation are just labelled, rather than explained. What gives rise to exploratory or exploitatory behaviour in the first place? How does an agent know when to switch from one to the other, and how do exploration and exploitation work? We don't know. The proposed schema further assumes that exploration and exploitation do not involve cognitive control, which stands in direct contradiction to recent theorizing. In fact, exploration and exploitation are often considered strategies of cognitive control (Cohen, McClure, & Yu, 2007). They are assumed to address a basic control dilemma that agents are facing (how much, how long to exploit, and when to explore?), alongside similar dilemmas like the persistence/flexibility dilemma or the speed/accuracy trade-off. Adaptive behaviour requires agents to find the right balance between the respective two extremes and to integrate individual goals with situational demands (Eppinger, Goschke, & Musslick, 2021; Goschke, 2003).

From this perspective, disinhibition and hyper-inhibition represent just another version of these basic dilemmas. And yet, the authors fail to recognize the connection between this dilemma, the other similar control dilemmas that are discussed in the literature, and the mechanisms that have been proposed to underlie them. For instance, the metacontrol state model (Hommel, 2015; Hommel & Wiers, 2017) addresses how agents balance between two opposing control strategies: Persistence and flexibility. Persistence is characterized by top-down bias from current goals and a strong mutual inhibition between competing alternatives, while flexibility is characterized by weak support from current goals and weak mutual inhibition. The mechanisms responsible for persistence and flexibility may or may not entirely overlap with mechanisms underlying exploitation and exploration, but there is evidence to suggest significant commonalities (van Dooren, de Kleijn, Hommel, & Sjoerds, 2021), and the mechanistic underpinnings of metacontrol can easily account for how disinhibition and hyper-inhibition may work (see Hommel & Colzato, 2017; Mekern, Hommel, & Sjoerds, 2019).

Hence, while we certainly believe in the importance of viewing different forms of human behaviour, including pathological manifestations, as a result of an interaction between different control dilemmas along a continuum, we feel that the approach put forth in the target article begs many important theoretical questions in its current form. Most importantly, we recommend replacing mere labelling with true mechanistic considerations, which can be found in the literature on cognitive control.

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Question-asking as a mechanism of information seeking

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Abstract

Ivancovsky et al. explore the relationship between curiosity and creativity, by suggesting they align through novelty-seeking mechanisms. We argue that a general mechanism linking both capacities together is question-asking: Curiosity drives question-asking that leads to creative problem solving. Yet, current findings from our lab suggest that question complexity relates to creativity, but not necessarily to curiosity, warranting further investigation.

The article by Ivancovsky, Baror, and Bar is a timely article that aims to link curiosity and creativity under an information-seeking behavior framework. We agree with the sentiment and arguments raised by the authors, recently publishing a similar theoretical argument (Kenett, Humphries, & Chatterjee, 2023) as well as revised theories – on associative thinking and the role of memory in creativity – directly related to issues raised in the target article, but not discussed in it (e.g., Beaty & Kenett, 2023; Benedek, Beaty, Schacter, & Kenett, 2023).

We aim to highlight a critical issue not discussed in the target article, yet extremely important to its topic. The authors state: "The crux of our proposal is that curiosity and creativity converge on novelty seeking mechanisms…" and that "We propose that both are manifestations of a unified process that underlies novelty-seeking, as illustrated by a novelty-seeking model" (Ivancovsky et al.). While curiosity might be the driver, and creativity the output, of such information-seeking behavior, what mechanism realizes the *seeking* aspect of this behavior?

Information-seeking behavior likely promotes *problem finding*, the first stage in the creative problem-solving process (Reiter-Palmon & Robinson, 2009). Operationally, it involves the identification of a problem or the definition of an ambiguous situation into a workable problem or the raising of questions from ill-defined problem situations (Getzels, 1979). Past research indicates that problem finding is positively related to creative problem-solving (Mumford, Medeiros, & Partlow, 2012) and to divergent thinking measures of creativity (Abdulla, Paek, Cramond, & Runco, 2020; Alabbasi, Acar, & Reiter-Palmon, 2023). Reiter-Palmon, Mumford, O'Connor Boes, & Runco (1997, 1998) have found that people who excel at problem-finding tend to restate problems as questions, highlighting the significance of questions in creativity.

We aim to expand and enrich the discussion of the target article on linking curiosity and creativity as information-seeking behavior, by highlighting the role of question-asking in such behavior. While we commonly and constantly ask questions, little research has been conducted on why humans ask questions and how question-asking facilitates information-seeking behavior. Questions are essential in human interactions, from children to adults (De Simone & Ruggeri, 2021; Ruggeri, Lombrozo, Griffiths, & Xu, 2016; Ruggeri, Xu, & Lombrozo, 2019). They are widely used in a major part of our conversations, and have been shown to improve likability and engagement (VanEpps & Hart, 2022). Questions also support our efforts to acquire knowledge and solve problems (Gottlieb, 2021; Rothe, Lake, & Gureckis, 2018).

Asking questions has also been suggested to serve as an indicator of curiosity, which has been found to be related to creativity. Curiosity plays an important role in the creative process, particularly when it comes to questions that reflect the sense of wonder that is intertwined with creativity (Acar, Berthiaume, & Johnson, 2023). Thus, one may ask: What is the role of question-asking in creativity? How does curiosity drive question-asking which leads to creative problem solving? In our lab, we focus on this issue, via computational and empirical research.

In one line of research, we conducted an exploratory data analysis on the questions asked by an online question-asking game known as the Akinator (Sasson & Kenett, 2023). In this game, a Genie like character attempts to guess the character the human player is thinking of, by asking a series of yes/no questions. We examined the types and sequencing of questions asked by the Akinator, to gain insights into natural human question-asking.

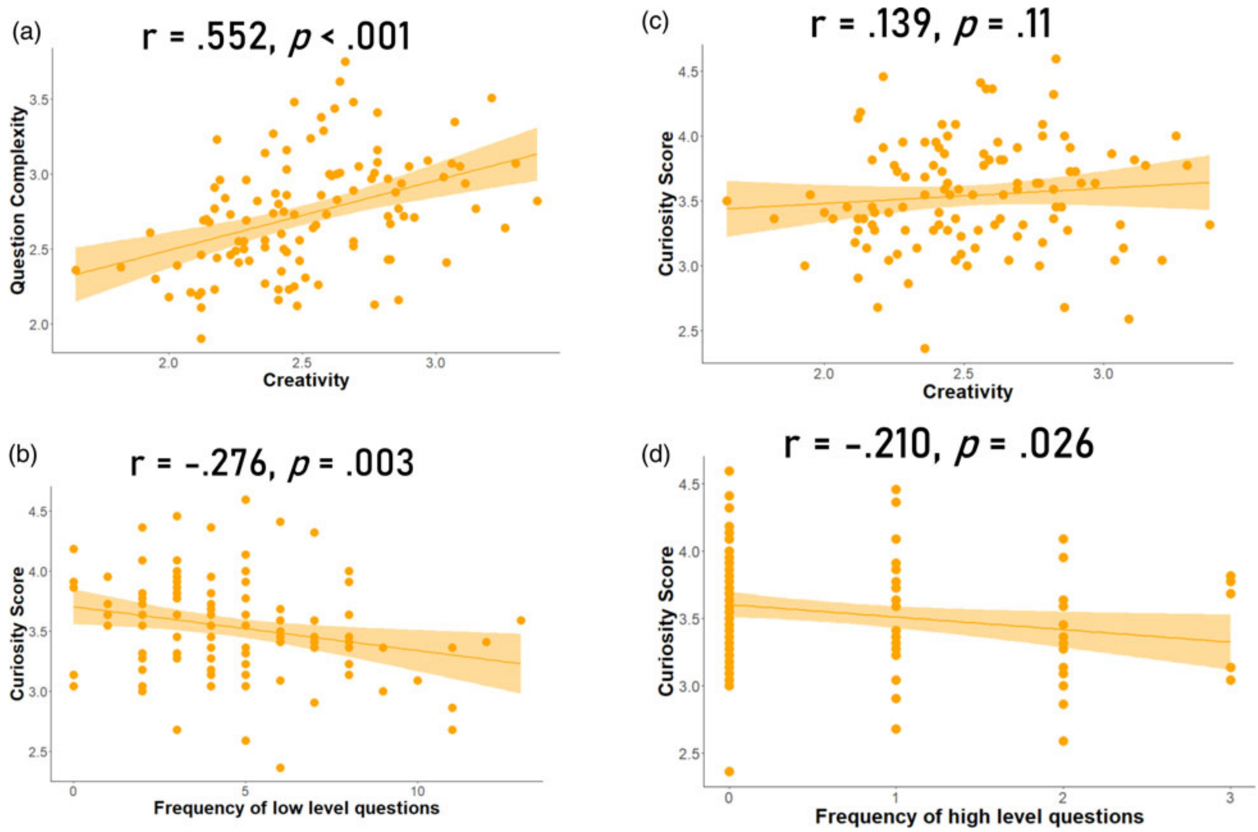

Figure 1 (Raz and Kenett). Scatter plots of data reported in Raz *et al.* (2023) between: (A) Question complexity and creativity; (B) creativity and curiosity; (C) low-level questions and curiosity; (D) high-level questions and curiosity.

While our analysis was limited in scope due to IP protection, we demonstrate that the Akinator's question-asking process does not aim to narrow an information space – a popular theory on the aim of question-asking – and that the questions generated by the Akinator can be characterized into focused, yet time-evolving, topics.

In a second line of research, we directly examine the role of asking more complex questions in creativity (Raz, Reiter-Palmon, & Kenett, 2023). We adapt the popular in-lab creativity assessment task – the alternative uses task (Acar & Runco, 2019) that assesses divergent thinking. Divergent thinking is defined as ones' ability to generate multiple solutions to a given problem and is considered a main component of creative thinking. In the alternative uses task, participants are presented with an object and are required to generate all alternative uses possible for that object. In our revised task, we present participants with common objects such as a pencil or pillow, and are required to generate all the possible questions they can ask about that object. We then use subjective and objective assessments of participant's creative performance in both tasks, as well as rate each of the questions for their complexity (based on a classic complexity taxonomy known as the Bloom taxonomy; Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956). We find that as participants ask more complex questions, they are more creative, empirically highlighting the role of question-asking in creativity. In addition, participants are also assessed for intelligence, Openness to Experience, and curiosity (Raz *et al.*, 2023). Although we find a strong significant relationship between question-asking and creativity, we find that in general, creativity was not significantly related to curiosity, further highlighting the complex relation between them (Gross, Zedelius, & Schooler, 2020). Finally, we find significant negative relations with question complexity and curiosity (as measured via self-report questionnaires) for both low- and high-level (complex) questions (Fig. 1).

Overall, question-asking is a possible mechanism that links together creativity and curiosity as related to information-seeking behavior. Yet, our findings demonstrate differentiated – and surprising – relations between question-asking, curiosity, and creativity. Thus, our current findings highlight the complex, largely unknown, relations between these capacities. Such results indeed raise more questions than answers, calling for empirical research to further elucidate the relation between them. Nevertheless, any theoretical framework on this topic, such as that by Ivancovsky et al., requires addressing specific mechanisms that drive such information-*seeking* behavior. Question-asking is likely such a mechanism, one that should not go unnoticed.

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Commentary on creativity and curiosity

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Abstract

The target article covers a large amount of ground and offers a provocative perspective. This commentary focuses on (a) assumptions, namely that there are discrete stages in the creative process and that novelty and usefulness are inextricable, (b) hidden variables in the creativity–curiosity relationship, and (c) the difference between an *explanation* of creativity versus a description of *influence* on it.

Science advances as data are collected and theories built. Meaningful data are empirically reliable. Useful theories are consistent with data, coherent, and comprehensive. Ivancovsky et al. cite empirical findings on tolerance, novelty, openness, cognitive control, attention, and more, as they build a theory to explain the relationship of creativity with curiosity (C&C). The theory is consistent with data and is comprehensive. There are, however, several assumptions. They may be safe assumptions, but those assumptions should be recognized for what they are, namely, claims with some support but also some uncertainty.

Consider in this regard the idea that the usefulness of an idea or solution is only found after novelty. Following Wallas (1926), the creative process has almost always been described as sequential (with stages). Thus the assumption made by Ivancovsky et al. is neither surprising nor risky. Still, care must be taken when extricating what is involved in creativity. Even if stages can be isolated, that may not be the way creativity actually operates in the natural environment. Consider the claim, "problem solvers must also find a way to manage usefulness after establishing novelty" (target article, sect. 5.1, para. 4). This implies clear separation. In reality the process may be iterative (Runco, 1994).

To their credit Ivancovsky et al. "hope that the theoretical framework proposed here may apply to curiosity and creativity 'in the wild'" (target article, sect. 1, para. 2). They are thus aware of controlled research versus the natural environment (which is what I assume they mean by "in the wild"). Perhaps this is why one of the citations ostensibly supporting the novelty-usefulness separation (Berg, 2014) is a book about "Commerce and creativity in eighteenth-century Birmingham." Litchfield's (2008) study of brainstorming is also cited as support for the claim that usefulness follows novelty. Yet quite a bit of evidence suggests that brainstorming is not entirely successful (Rickards & deCock, 2003). This may be because of the difficulty people have when postponing evaluation (which usually focuses on whether or not an idea is useful) while working in groups. Very likely, the creativity that occurs in the natural environment involves iteration, whereby the individual thinks of an idea, and then evaluates it, and uses that evaluation to find a second idea, and then evaluates it, and so on.

There is even a possibility that originality and usefulness are simultaneous and depend on one process (i.e., the creativity process)! Ivancovsky et al. believe that novelty and usefulness "require different abilities" (target article, sect. 5.1, para. 4), but it is not farfetched to think that ideas are produced only if they are somehow relevant to the task at hand. The human mind may very well generate ideas that are simultaneously rather than sequentially original and useful (Runco, 2010). Most models view them as sequential (e.g., Campbell, 1960; Simonton, 2023) but the simultaneous possibility has not been ruled out.

Novelty (or originality) and usefulness are required by the *standard definition of creativity* (Runco & Jaeger, 2012). Originality presumably results from idea generation and usefulness from evaluation. The assumption here is that "usefulness refers to the practical qualities, acceptance by other people, and adherence to cultural norms" (target article, sect. 5.1, para. 4). That is not accurate. Creativity is often personal (Runco, 2019), and when it is, usefulness is independent of acceptance by other people. The same holds for most of *everyday creativity* (Richards, 2007). Further, usefulness varies from domain to domain. In the arts, it is often an aesthetic usefulness and unrelated to practical function or norms.

It would help if the explanations uniquely explained C&C. Supposedly C&C "act similarly across multiple domains, reflecting their proposed connection" (target article, sect. 2, para. 1), but there are other things that act similarly across domains (e.g., persistence, openness). Then there are "the same brain regions [which] are involved in both curiosity and creativity" (target article, abstract). This assumes localization, so the authors quickly acknowledge "an interplay" involving the default, salience, and executive control networks, but those too are not uniquely devoted to C&C. This also does little to support their interdependency.

These illustrations imply a parallel with correlational research where X and Y are related to one another but only because they are both dependent on Z. Ivancovsky et al. are quite close to this situation when they discuss the reward regions in the brain, and closer still with "curiosity and creativity rely on shared attentional mechanisms" (target article, sect. 2.3, para. 1). The word "rely" implies that attention is vital, but what of the creative breakthroughs found when the individual incubates and attends to something other than the problem? Even if both C&C rely on attention, in the case of creativity, attention is probably like motivation (Amabile, 1990; de Jesus, Rus, Lens, & Imaginário, 2013): It is involved up front and no unique to creativity.

Ivancovsky et al. also assume that creativity is dependent on knowledge. This too not a bad assumption. It is in line with various theories, and there are supporting data. There are, however, alternative possibilities which have not been entirely refuted. Emergence, nonlinear thinking, and assimilation may each provide new insights without relying on the recombination of existing knowledge (Runco, 2023). Sure, they are difficult to test (Schaeffer, Miranda, & Koyejo, 2023). It may not be an either/or situation, given that knowledge is retained in memory, and memory can itself be constructive, meaning that new elements may be introduced. Episodic memory sometimes adds new material to memory, for instance, filling in the gaps between bits of actual experiences. Fabrication is not uncommon.

Is this theory of curiosity more compelling than models of intrinsic motivation (Amabile, 1990; de Jesus et al., 2013)? Either way, all we have is a partial explanation. Curious individuals may be persistent and direct efforts toward novelty and the other things required for creativity, but to say that people are creative because they are curious does not explain *how* the mind creates. It probably creates using divergent thinking, insight, and perhaps nonlinear or emergent processes. These are brought to bear on problems because of the curiosity or intrinsic motivation, but there are other requirements. This is why creativity is described as a complex (Mumford & Gustafson, 1988) or syndrome (MacKinnon, 1965). Curiosity at most tells us why, not how.

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An extension of the novelty-seeking model: Considering the plurality of novelty types and their differential interactions with memory

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Abstract

The novelty-seeking model suggests that curiosity and creativity originate from novelty processes. However, different types of novelty exist, each with distinctive relationships with memory, which potentially influence curiosity and creativity in distinct ways. We thus propose expanding the NSM model to consider these different novelty types and their specific involvement in creativity.

The innovative novelty-seeking model (NSM) by Ivancovsky et al. states that novelty-seeking processes are at the root of curiosity and creativity. Ivancovsky et al. distinguish four phases in their NSM model. Firstly, affinity, and therefore attention to new internal or external stimuli, generates new combinations within the existing semantic knowledge network. Secondly, this new associative representation is activated, and thirdly, when the representation exceeds the salience threshold, the evaluation of its relevance takes place. Fourthly, the new relevant representations are consolidated in the semantic memory network. In this commentary, we would like to comment on the role of memory, a significant component of the NSM, since the authors stress its importance by stating that their model originates and ends in memory.

By stating that the NSM starts in memory, the authors refer to the activation of prior knowledge. However, they also mention a role for episodic memory, which appears to be unclear. By definition, detecting novelty relies on distinguishing the new from the familiar. Novelty processing is thus closely tied to prior knowledge, which is of great interest because prior knowledge forms the groundwork for determining the types of new information that need to be best consolidated in memory. Recent studies (Quent, Greve, & Henson, 2022) have shown that the link between memory consolidation of new information and their congruency with prior knowledge is a non-linear U-shape function: Highly congruent and highly incongruent information will be remembered better than less (in)congruent. Note that, for a long time, the two ends of this U-shape have been studied as two distinct fields of research: The congruency effect in memory on the one hand and the surprise effect on memory on the other.

Interestingly, information at the two extremities of the U-shape activates different brain regions at encoding (van Kesteren, Ruiter, Fernández, & Henson, 2012): While processing information, the medial prefrontal cortex either triggers rapid learning of schema-congruent information into the neocortex or activates the hippocampus in the medial temporal lobe to encode schema-incongruent events. However, differences in memories are also suspected at retrieval as remembering incongruent events engages the network for source memory (Brod, Lindenberger, Werkle-Bergner, & Shing, 2015). We, therefore, hypothesize that the two ends of the U-shape are linked to different memory systems: While congruent information is supposed to be stored as semantic representations, incongruent information is thought to induce episodic memories – that are memories of unique personal past experiences with their spatiotemporal context. Even more interestingly, the two tales of the U-shape are likely to rely on different novelty types. As the current literature on novelty tends to revise terminology and identify different subtypes of what is generally understood under the term "novelty" (e.g., Bastin, Delhaye, Moulin, & Barbeau, 2019; Kafkas & Montaldi, 2018), this is another prominent point to which we would like to draw attention. Since prior knowledge determines novelty type and further modulates how novelty impacts memory (Frank & Kafkas, 2021), we believe that considering different subtypes of novelty and memory systems is relevant for the NSM.

By citing the work of Duszkiewicz, McNamara, Takeuchi, and Genzel (2019), Ivancovsky et al. briefly evoke the existence of different types of novelty and the potential role of episodic memory. Specifically, Duszkiewicz et al. (2019) proposed that novel experiences classified as *common novelty*, which share similarities with congruent past experiences, facilitate the formation of semantic memories in contrast to experiences classified as *distinct novelty*, which have minimal connections with past experiences and result in the creation of contextualized specific episodic memories. However, we regret that these aspects have yet to be integrated further into the NSM, which primarily focuses on the semantic network and does not differentiate novelty types. Indeed, different types of novelty modulate the environment's uncertainty and memory encoding and consolidation differently (Quent, Henson, & Greve, 2021) – the processes pointed out by the authors as cognitive underpinnings of creativity and curiosity.

Although we agree with Ivancovsky et al.'s central claim that novelty-seeking processes mediate curiosity and creativity, we call for a distinction between different types of novelty that could interact differently with curiosity or creativity and lead to memory representations of different natures. Specifically, if both common and distinct novelty are known to attract attention and thus lead to a curiosity state, their respective link with creativity may seem less straightforward. On the one hand, common novelty fits the typical situation described by the authors: The new information congruent with prior knowledge will be combined with prior semantic knowledge to fill an existing gap within the associative semantic network. On the other hand, distinct novelty, a good candidate for creativity as its high incongruence naturally provides novel original associations, is thought to induce episodic memories. Although most of the research on creativity has focused on semantic memory, researchers have recently demonstrated the role of episodic memory in creative processes (Beaty et al., 2020) as well as its interaction with semantic memory during divergent thinking (Ramey & Zabelina, 2021).

To conclude, given that semantic and episodic memory systems may be linked to different types of novelty, and given that novelty is at the heart of the NSM model, we would suggest adding the impact of episodic memory in the NSM. This addition will help increase the completeness of the model to make it generalizable to as many novelty-seeking situations as possible. This would also have implications for the consideration of clinical perspectives. Beyond psychopathology, the NSM could also address the case of brain-damaged patients with memory problems and the fact that they present decreased creativity (Duff, Kurczek, Rubin, Cohen, & Tranel, 2013).

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Creativity is motivated by novelty. Curiosity is triggered by uncertainty

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Abstract

Although creativity and curiosity can be similarly construed as knowledge-building processes, their underlying motivation is fundamentally different. Specifically, curiosity drives organisms to seek information that reduces uncertainty so that they can make a better prediction about the world. On the contrary, creative processes aim to connect distant pieces of information, maximizing novelty and utility.

Ivancovsky et al. proposed that curiosity and creativity are processes that are likely to be closely linked. Indeed, we agree that both processes share similar exploration–exploitation mechanisms. Some may argue that there is a primary difference: Creative processes tend to be an exploration–exploitation for *internal* knowledge representation, whereas curiosity processes focus more on the exploration–exploitation of *external* information. However, both processes have the critical commonality that they are purported to build up the knowledge, either by seeking information internally or externally.

We have one critical comment, however. The proposed model has a fundamental assumption that novelty seeking is the key element underlying these two processes. In fact, the authors indicated "the underlying motivation of curiosity and creativity is novelty seeking" (target article, sect. 2.6, para. 4). We do not have any objection to the role of novelty seeking in creativity processes. However, we are not sure whether this is the shared view in the research on curiosity. Although curiosity is supported by multiple distinct types of motivation (Kobayashi, Ravaioli, Baranès, Woodford, & Gottlieb, 2019), one common view is that curiosity drives people to seek information that reduces *uncertainty* (Fitzgibbon & Murayama, 2022; van Lieshout, de Lange, & Cools, 2021). Uncertainty reduction is distinct from novelty seeking. In fact, people are often curious about the things that they are highly *familiar* with. In studies on interest in educational psychology, when participants are free to choose topics to learn about, they often opt for subjects they are already knowledgeable in (Alexander, Kulikowich, & Schulze, 1994; Fastrich & Murayama, 2020; Tobias, 1994).

Putting it from the knowledge network perspective (Murayama, 2022; Patankar et al., 2023) people often feel curious when they perceive the potential for adding new edges between semantically *close* concept nodes. More specifically, people tend to become curious when two concepts are closely related but feel that some important information is missing to connect these two concepts – that is, when people are aware of the *knowledge gap* (Loewenstein, 1994; Patankar et al., 2023). Consistent with this idea, in studies on curiosity that inform participants about knowledge gaps and ask if they can guess the missing information, curiosity is strongly positively associated with their confidence in their guess (Kang et al., 2009; Metcalfe, Schwartz, & Bloom, 2017; Singh & Manjaly, 2021). In other words, their curiosity was highest when they felt familiar with the answer but could not retrieve it (Litman, 2005).

Why? This is because curiosity motivates organisms in a way that efficiently reduces uncertainty, so that organisms can make good predictions about the world and quickly adapt to the environment (Schwartenbeck et al., 2019). People are especially keen to fill the knowledge gap of a familiar topic because this missing information is likely to provide a bigger marginal gain in terms of understanding the topic. It is true that curiosity sometimes drives organisms to seek novel information, but this is mostly not because they are novel, but because such novel information often reduces the uncertainty. The goal is different.

We are not sure if this fundamental aspect of curiosity maps onto creativity processes. Creativity involves the capacity to generate an output that is *semantically distant* from the input or stimuli provided, yet remains meaningful, appropriate, or useful within the context of a given task. In other words, creativity motivates people to take substantial semantic leaps away from the current stimuli and connect the pieces of information that were far apart, while considering the constraints of utility. Uncertainty reduction, or more ultimately, accurate representation of the world does not seem to be the main function of creativity processes.

Note also that this strategic uncertainty reduction in curiosity does not map onto the exploitation (i.e., goal-directed) aspect of exploitation–exploration continuum the authors proposed. In a sense, all curiosity-motivated behavior can be regarded as goal directed (i.e., they serve to efficiently reduce uncertainty), and in fact, curiosity is often characterized as a strategic or "directed exploration" (Jach et al., 2023). The distinction between exploitation and exploration is somewhat blurred and arbitrary from the perspective of uncertainty reduction (Murayama, FitzGibbon, & Sakaki, 2019), while we agree that the distinction has a heuristics value to understand the phenomenon.

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A developmental account of curiosity and creativity

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Abstract

Ivancovsky et al.'s Novelty-Seeking Model suggests several mechanisms that might underlie developmental change in creativity and curiosity. We discuss how these implications both do and do not align with extant developmental findings, suggest two further elements that can provide a more complete developmental account, and discuss current methodological barriers to formulating an integrated developmental model of curiosity and creativity.

Curiosity and creativity are defining features of early childhood (Lucca & Wilbourn, 2018; Mottweiler & Taylor, 2014) that are widely believed to fade with age – a worrying prospect, given how essential they are for discovery and innovation (Gopnik & Griffiths, 2017). Evidence for such worries, however, is mixed; while some studies suggest developmental decreases in curiosity and creativity (e.g., Liquin & Gopnik, 2022), others indicate improvements (e.g., Said-Metwaly, Fernández-Castilla, Kyndt, Van Den Noortgate, & Barbot, 2021). We suggest Ivancovsky et al.'s Novelty-Seeking Model (NSM) – specifically the proposed role of top-down processes – can help reconcile these findings. We discuss how the NSM's predictions both align with and deviate from existing developmental research and propose two new elements that, if integrated into the NSM, could help it more fully explain creativity and curiosity across the lifespan.

The NSM ascribes a central role to top-down attentional and cognitive control. The profound improvement in these capacities from infancy to adulthood (Carlson, Zelazo, & Faja, 2013) suggests their development is integral to developmental change in creativity and curiosity. At the affinity stage of the NSM, children's broader, less focused attention might allow more stimuli to draw their attention and trigger the novelty-seeking process, expanding the scope of exploration. At the evaluation stage, children's limited executive function skills might constrain their ability to evaluate ideas (in creativity) or focus on and deeply explore them (in curiosity), leading to more expansive but less refined creative ideation and broader but shallower exploration. In sum, rather than monotonic developmental increases or decreases, the NSM implies different patterns of change in different aspects of creativity and curiosity – breadth and volume should decrease with age, as top-down control strengthens, but depth and quality should increase.

In many respects, these NSM-based predictions are consistent with existing developmental findings. Consistent with the NSM's account of the affinity stage, children explore new environments more broadly than adults (Liquin & Gopnik, 2022), at least partly due to their wider attentional scope (Blanco & Sloutsky, 2020; Plebanek & Sloutsky, 2017). And consistent with the NSM's account of the evaluation stage, there is evidence that children can use their executive function skills to increase the creativity of their ideas, but do so less effectively than adults (Nusbaum, Silvia, & Beaty, 2014; Vaisarova & Carlson, 2023).

Other developmental findings, however, are harder to reconcile with the NSM. Perhaps most notably, the NSM implies children should be better at generating many ideas (i.e., more creatively "fluent") than adults due to their broader attentional scope and limited capacity for idea-evaluation. However, except for some temporary "slumps," ideational fluency generally increases with age (Said-Metwaly et al., 2021). While this discrepancy might be partly explained by developmental change in the content and structure of memory, it remains unclear whether this is the full story. Further, in contrast with positive associations between adults' executive function and fluency (e.g., Benedek, Franz, Heene, & Neubauer, 2012), children's executive function can be negatively associated with fluency (Hendry et al., 2022; Vaisarova & Carlson, 2021). This suggests qualitative change in the role of top-down processes, which the NSM does not currently account for. We propose the model needs to incorporate additional factors – including metacognitive skills and social influences – to apply across the lifespan.

Developmental change in metacognition – specifically, understanding of one's own novelty-seeking process – can help contextualize the changing role of executive function. While adults self-report using a range of executively demanding strategies when generating ideas (Gilhooly, Fioratou, Anthony, & Wynn, 2007), children report fewer, less executively demanding strategies (Bai, Mulder, Moerbeek, Kroesbergen, & Leseman, 2021). Understanding how to strategically enhance ideation appears to improve with age and might shape how executive function is used at the NSM's evaluation stage – not just to evaluate ideas, but to evaluate and modify the novelty-seeking process. Metacognitive changes can also help explain the finding that executive function appears positively associated with adults' ideational fluency but negatively associated with children's; this might occur because adults better understand how to use their executive skills to help them generate ideas.

A second factor emphasized in developmental discussions of creativity and curiosity, which would enrich the NSM and help it better account for developmental findings, is the social context in which novelty-seeking unfolds. Social conformity and social learning are key factors that can both constrain and expand creativity and curiosity (Barbot, Lubart, & Besançon, 2016; Lee, Lazaro, Wang, Şen, & Lucca, 2023). For instance, children's artwork becomes less creative when they are told it will be evaluated (Amabile, 1982), and when parents engage in more exploration their children do as well (Willard et al., 2019). Within the NSM, we propose these influences largely operate at the affinity and evaluation phases. Social cues may draw individuals' attention to certain aspects of their environment, as well as shaping their goals and evaluation criteria. Standards for the usefulness of an idea, for instance, might be higher in a context where it will be used by others.

Our discussion is limited by methodological factors that have precluded researchers from giving equal attention to creativity and curiosity across ages, making it difficult to pinpoint their associations and shared processes across development (but see Evans & Jirout, 2023). Creativity assessments tend to rely heavily on verbal skills, making them inappropriate for very young children, while curiosity-driven behaviors like pointing and manual exploration can be reliably observed in infancy (Lucca & Wilbourn, 2018; Stahl & Feigenson, 2015). And although both curiosity and creativity are multidimensional and pose significant measurement challenges (Lee et al., 2023; Lubart, Zenasni, & Barbot, 2013), development of behavioral creativity assessments for children has received more attention (e.g., Torrance, 1966). Ongoing work in our research group aims to address this discrepancy by developing a behavioral "curiosity battery" for young children. A complete account of mechanisms underlying curiosity and creativity across the lifespan will require research examining their links from an early age using validated, developmentally appropriate measures, and considering the role of factors like metacognition and social context. Beyond providing a more robust theoretical model, this work has important practical implications – the more we know about how curiosity and creativity operate early in life, the more we can empower children to become curious, creative problem-solvers.

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Mood regulation as a shared basis for creativity and curiosity

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Abstract

We extend the work of Ivancovsky et al. by proposing that in addition to novelty seeking, mood regulation goals – including enhancing positive mood and repairing negative mood – motivate both creativity and curiosity. Additionally, we discuss how the effects of mood on state of mind are context-dependent (not fixed), and how such flexibility may impact creativity and curiosity.

Ivancovsky et al. proposed that both creativity and curiosity are motivated by the desire to experience novelty (novelty seeking). We propose that, in addition to novelty seeking, the desire to regulate one's mood (i.e., enhance positive mood and/or reduce negative mood) is another mechanism that motivates both creativity and curiosity. Thus, we review empirical evidence to describe how creativity and curiosity are both driven (in part) by mood regulation goals. Further, we highlight how mood flexibly alters state of mind (SoM) to shape creativity and curiosity.

Curiosity typically involves feelings of interest (diversive curiosity) or feelings of deprivation (specific curiosity) – both motivate information seeking (that is expected to be rewarding) as a means of potentially regulating mood (Litman, 2005). Diversive curiosity is driven by interest (a positive emotion; Silvia, 2006) and thus often involves positive mood (Litman, 2008; Sung, Yih, & Wilson, 2020). People experiencing these positive states are motivated to maintain/enhance them, and thus engage in broad information seeking in anticipation of finding rewarding (e.g., novel) information (Litman, 2005). Specific curiosity stems from the desire to reduce unpleasant mood evoked by a perceived knowledge gap (Litman, 2008; Litman & Jimerson, 2004) – people in such negative states engage in narrow information seeking in anticipation of finding the information needed to close the knowledge gap and repair their negative mood (Litman, 2005; Lydon-Staley, Zhou, Blevins, Zurn, & Bassett, 2021). We therefore agree with the assertion of Ivancovsky et al. that diversive curiosity typically involves an exploratory SoM and positive mood, whereas specific curiosity involves an exploitatory SoM and reduction of negative mood. However, despite the underlying assumption that curiosity is driven by interest (to increase positive mood) or deprivation (to decrease negative mood), few studies have examined curiosity in the context of mood regulation or real-world emotional experience, making this a fruitful area for future research.

Crucially, much like curiosity, creativity also is commonly driven by the desire to enhance positive moods and/or reduce negative moods, and it is effective at doing so (Conner, DeYoung, & Silvia, 2018; Zhai et al., 2021). For example, people often report feeling joy and satisfaction after generating creative products (Forgeard & Eichner, 2014). Additionally, creativity in daily life is frequently intrinsically motivated and involves flow (Zeitlen, Silvia, Kane, & Beaty, 2022), an inherently rewarding state. Notably, flow states typically produce strong positive moods, and people pursue various (e.g., creative) activities to experience such rewarding states (Engeser & Schiepe-Tiska, 2012). Taken together, these findings suggest that creativity is often a rewarding experience that people pursue to effectively increase their positive mood.

In addition to enhancing positive mood, creativity might be pursued to repair negative moods. For example, the ability to generate creative responses to a worrisome future problem reduces anxiety and negative mood (Jing, Madore, & Schacter, 2016). Furthermore, research on art therapy reveals that creating art can help people cope with and repair their negative moods (Bell & Robbins, 2007; Futterman Collier & Wayment, 2021). Indeed, creativity is a critical resource for resilience and coping with adversity (Orkibi, 2023). For example, the ability to generate new and adaptive responses to changed and/or stressful situations ("creative adaptability") positively predicts resilient coping, which in turn predicts decreased negative mood and greater well-being during periods of adversity (e.g., COVID-19 pandemic; Orkibi et al., 2021). Altogether, these findings indicate that people frequently engage in creative acts to help them effectively cope with and repair negative moods.

In addition to mood regulation goals, mood influences the processes involved in shaping both creativity and curiosity, but in a flexible way that depends on the information that mood provides within the context. For example, mood can promote information seeking by increasing the perceived value of information, such that negative mood increases goal-directed information seeking when task performance is perceived as strong, whereas positive mood increases such behavior when task performance is perceived as weak (Gasper & Zawadzki, 2013). Additionally, whether positive or negative mood promotes broad thinking and exploration depends on which processing styles are currently most accessible (dominant) in one's SoM. Positive moods signal that the dominant processing (e.g., perceptual/attentional) style is more appropriate to use (reinforcing its use) than do negative moods (which inhibit its use; Huntsinger, Isbell, & Clore, 2014). Thus, when a global processing style is dominant, positive moods promote the use of a global style and broad thinking, which typically leads to greater creativity; but when a local style is dominant, they promote the use of a local style and narrow thinking, which often results in less creativity (Huntsinger & Ray, 2016). Therefore, positive mood typically promotes an exploratory SoM (as there is a bias toward global processing; Navon, 1977), fostering creativity and diversive curiosity; but when a local style is dominant in one's SoM, then negative mood promotes an exploratory SoM and positive mood might promote an exploitatory SoM, fostering specific curiosity. Ivancovsky et al. did not address this nuance, in that they assumed the effects of mood on SoM were fixed, not flexible. Their novelty-seeking model linking curiosity and creativity might have greater predictive utility if it took into account the flexible nature of mood effects on SoM.

In sum, creativity and curiosity are both influenced by mood regulation goals and context-dependent effects of mood on SoM. Both novelty seeking (as proposed by Ivancovsky et al.) and mood regulation are shared bases for creativity and curiosity. This expanded framework could help to further elucidate the link between curiosity and creativity. Indeed, the anticipated reward of discovering novel ideas is one reason why people pursue their curiosity or creativity to regulate their mood. The emotional motivations underlying creativity and curiosity also extend beyond such novelty seeking (e.g., coping with negative mood by engaging with meaningful information). Future studies, which account for context-dependent effects of mood on SoM, are needed to directly assess shared (cognitive and emotional) motivations underlying curiosity and creativity. Such work would inform how novelty seeking and mood regulation, among other processes and influences (e.g., SoM), promote both creativity and curiosity.

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Expanding horizons in reinforcement learning for curious exploration and creative planning

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Abstract

Curiosity and creativity are expressions of the trade-off between leveraging that with which we are familiar or seeking out novelty. Through the computational lens of reinforcement learning, we describe how formulating the value of information seeking and generation via their complementary effects on *planning horizons* formally captures a range of solutions to striking this balance.

Ivancovsky et al. propose fruitful connections between curiosity and creativity under an exploration–exploitation trade-off. The explore–exploit trade-off is the decision between a familiar option with known value and an unfamiliar option with unknown or uncertain value (Addicott, Pearson, Sweitzer, Barack, & Platt, 2017). Choosing unfamiliar options is risking time, energy, and foregone reward in return for information (Rubin, Shamir, & Tishby, 2012).

These ideas have history in reinforcement learning. For example, novelty-seeking is important to prevent failures of learning where subpar solutions are settled on prematurely (Fox, Pakman, & Tishby, 2015). Despite the benefits of novelty-seeking, seeking novel information can also carry a high cost when forgoing familiar opportunities and accruing a burdensome amount of information (Wilson, Bonawitz, Costa, & Ebitz, 2021). Thus, one must manage costs by taking "sensible risks" which balance exploring to learn novel information about the environment with accruing increasingly complex information for different tasks at hand (Sternberg & Lubart, 1996). One way to encourage taking on these risks for exploration is to use heuristics which locally track what has and has not been seen (Tang *et al.*, 2017; Wittmann, Bunzeck, Dolan, & Düzel, 2007; Wittmann, Daw, Seymour, & Dolan, 2008). By contrast, preferring familiarity can manifest as a form of perseverative information seeking that was associated with deprivation curiosity (Lydon-Staley, Zhou, Blevins, Zurn, & Bassett, 2021), a drive to reduce uncertainty and acquire missing information (Kashdan *et al.*, 2018; Litman, 2008). This preference for familiarity has been seen as prevalent in people with greater depressed mood and anxiety (Zhou *et al.*, 2023), and may be an important heuristic strategy to reduce uncertainty for better reliability of future-oriented decisions (Harhen & Bornstein, 2023; Jiang, Kulesza, Singh, & Lewis, 2015). However, in large environments, such local heuristics are impoverished, particularly when higher-order associations are needed for planning. This need for richer measurements motivates the use of network science tools to formalize both local and global relationships as internal representations of the environment (Yoo, Bornstein, & Chrastil, 2023; Zhou, Lydon-Staley, Zurn, & Bassett, 2020). Thus, we propose expansions of the novelty-seeking model using reinforcement learning approaches to exploration and network science perspectives on information complexity and compression.

Ivancovsky et al. rightly note that curiosity and creativity must involve a dynamic policy of behavior that adaptively alternates between modes of exploration and exploitation. Reinforcement learning approaches reveal what behavior pattern, or policy, is appropriate for a given task and environment, for instance adapted to the sparsity of rewarding solutions (Gershman & Niv, 2015). To this end, the reinforcement learning approach of Harada (2020) was described. However, notably this paper reported that divergent and convergent thinking measures of creativity and the personality trait of openness to experience (a proxy for being "inventive/curious") were *not* robustly associated to exploration and exploitation behavior based on model-free reinforcement learning (Harada, 2020). This finding and other work (Jach *et al.*, 2023; Molinaro *et al.*, 2023) highlight the need for understanding creativity via more sophisticated models of the value of exploration.

The value of information is sometimes treated as a simple heuristic for predisposing choices toward exploration (Gottlieb, Oudeyer, Lopes, & Baranes, 2013), but the value can also be formally expanded as the change in future expected value that results from increasing certainty over representations of the environment and sequence of choices (Kaelbling, Littman, & Cassandra, 1998). These planning and policy iteration approaches aim for more global knowledge about the environment, and thereby differ from the local count-based reward functions to encourage exploration (Masís, Chapman, Rhee, Cox, & Saxe, 2023; Oudeyer & Kaplan, 2007; Tang *et al.*, 2017; Wittmann *et al.*, 2008). Here we focus on approaches that balance the increased long-run discounted expected value of knowledge with the cost of sampling (exploration) (Kaelbling *et al.*, 1998). To this end, the focus of choices shifts from an explore-or-exploit distinction to the iterative improvement of knowledge of the environment by testing predictions and simulations of future outcomes according to a given action policy (Gruber & Ranganath, 2019; Kobayashi, Ravaioli, Baranès, Woodford, & Gottlieb, 2019; Wilson, Wang, Sadeghiyeh, & Cohen, 2020; Dubey & Griffiths, 2020; Liquin & Gopnik, 2022).

We describe two areas of future research. First, creative insights can emerge from expanded planning horizons. Planning is commonly implemented as a search over a decision tree, wherein expanded horizons entail a deeper search in the tree. When the internal representation of information about the causal structure of the environment is accurate, longer planning horizons are useful. However, when the representation is incomplete, a smaller planning horizon compresses the policy space and prevents overfitting to past observations (Jiang *et al.*, 2015). Humans can search over more complex structures in knowledge representations (Yoo *et al.*, 2023). That knowledge may be more modular and compressible, allowing for the grouped representation of a more diverse chain of actions (Lai & Gershman, 2021; Momennejad, 2020; Patankar *et al.*, 2023; Schapiro, Rogers, Cordova, Turk-Browne, & Botvinick, 2013; Stachenfeld, Botvinick, & Gershman, 2017). The ability to use more complex knowledge structures may involve a spatial-like ability to navigate those structures (Rmus, Ritz, Hunter, Bornstein, & Shenhav, 2022), as well as a metacognitive ability to balance knowledge uncertainty with deeper planning (Schulz & Bonawitz, 2007; Wade & Kidd, 2019; Nussenbaum *et al.*, 2023). Indeed, a form of mental navigation that spans diverse spaces has been proposed to be linked with both creativity and curiosity (Aru, Drüke, Pikamäe, & Larkum, 2023; Eysenbach, Gupta, Ibarz, & Levine, 2018; Zhou *et al.*, 2023). Although such diversity and depth can decrease knowledge uncertainty, it comes at the cost of time and computational resources to accrue and update information. Computational cost motivates the next direction of research.

Second, creatively recombining knowledge benefits from unlearning or updating outdated knowledge. This form of creativity complements a type of curiosity that is characterized by deconstructing and rebuilding current structures (Zurn, 2021). When an agent seizes onto a supposedly optimal choice that is actually suboptimal, future resources must be used to unlearn those experiences (Fox *et al.*, 2015). This is precisely a problem that deprivation curiosity can exacerbate (Kruglanski & Webster, 2018; Zedelius, Gross, & Schooler, 2022). A solution to this problem involves aiming for simpler, compressed policies by chunking actions (Lai & Gershman, 2021). Compression involves smartly discarding some information to efficiently redescribe the information, such as by describing an elephant and a chicken with one joint description rather than describing each alone (Cover & Thomas, 1991; Mack, Preston, & Love, 2020). In order to modulate the planning horizon, policies could be compressed to increase certainty, albeit over an impoverished model. This idea is related to strategically decomposing, aggregating, and reducing sequences of actions into a hierarchy of "options" (Botvinick, Niv, & Barto, 2009; Sutton, Precup, & Singh, 1999) to balance the growing cost of planning (Botvinick, 2012; Correa, Ho, Callaway, Daw, & Griffiths, 2023). The idea also relates to a computational form of curiosity that involves improving prediction of expected long-term value (Gruber & Ranganath, 2019; Schmidhuber, 2008). Prediction is related to compression because the best compression is the true data generating model, and the true data generating model is the most predictive (Shannon, 1948). Notably, neural activity has been measured to be most compressed in the default-mode network (Mack *et al.*, 2020; Zhou *et al.*, 2022), a network of regions central to the proposed

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novelty-seeking model. Default-mode activity is also associated with the simulation of hypothetical episodes (Schacter & Addis, 2007) and the replay of episodic memories (Schapiro, McDevitt, Rogers, Mednick, & Norman, 2018), which can help to plan or update actions from new experiences (Kauvar, Doyle, Zhou, & Haber, 2023; Wilson *et al.*, 2020).

In conclusion, curiosity could be thought of computationally as actions taken to justify the expansion of one's planning horizon. The consequent cost of increased complexity can be managed by creatively compressing action policies, which further supports the pursuit of long-term goals.

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Authors' Response

A shared novelty-seeking basis for creativity and curiosity: Response to the commentators

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Abstract

In our target article, we proposed that curiosity and creativity are both manifestations of the same novelty-seeking process. We received 29 commentaries from diverse disciplines that add insights to our initial proposal. These commentaries ultimately expanded and supplemented our model. Here we draw attention to five central practical and theoretical issues that were raised by the commentators: (1) The complex construct of novelty and associated concepts; (2) the underlying subsystems and possible mechanisms; (3) the different pathways and subtypes of curiosity and creativity; (4) creativity and curiosity "in the wild"; (5) the possible link(s) between creativity and curiosity.

R1. Introduction

In our target article, we proposed and substantiated a link between curiosity and creativity and outlined a novelty-seeking model (NSM) that underlies them both. We further suggested that the manifestation of the NSM is governed by one's state of mind (SoM) and demonstrated how this interplay may result in different subtypes of curiosity and creativity. We received 29 intriguing and thoughtful comments from varied research domains, which helped us examine our suggested theoretical model from a broader perspective, while clarifying and alluding to ideas that might have not gotten enough attention in the original article. This enriched the discussion in several important directions.

First, although novelty was first discussed as a relatively monolithic concept, in section R2 we address novelty in more depth and emerges as a multi-faceted concept that is intimately linked with other cognitive dimensions, such as learning, uncertainty, and familiarity. Thus, novelty seems to influence creativity and curiosity in many nuanced ways. Second, several specific subsystems and mechanisms have been raised by the commentaries in reference to our theoretical proposal. These include the division of semantic and episodic memory systems, the default mode network (DMN)/executive control network (ECN) neural systems, dynamic thresholds, and accounts based on metacontrol, mood or developmental changes. We discuss these potential mechanistic accounts in light of the reviewed findings in section R3. Third, in section R4, the expanded discussion following the commentaries resulted in a more parceled framework, with the understanding that factors like usefulness or persistence might pave pathways to different subtypes of curiosity and creativity. Fourth, in section R5, the link between curiosity and creativity is now broadened to include the naturalistic lens outside the lab, with stimulating examples of what drives novelty processes in poetry, art or music appreciation. Lastly, some critical commentaries expressed concern about whether the explored evidence is sufficient for substantiating the NSM. In section R6, we discuss the possible link(s) between curiosity and creativity in more detail. The response discussion below is organized by these five central theoretical and practical issues, addressing the raised suggestions, and highlighting the remaining open questions.

R2. Novelty is a complex construct

The target article proposed the NSM as the fundamental underlying basis for creativity and curiosity. While we referred to novelty in a rather generalized manner, we acknowledge that novelty is heterogeneous and that the kind of information in each case and context determines the novelty type (Kafkas & Montaldi, 2018), in line with findings from novelty detection research.

As suggested by some of the commentaries (e.g., **Servais & Bastin**; **Omigie & Bhattacharya**; **Holm & Schrater**; **Becker et al.**; **Jirout et al.**; **Singh & Murayama**), the distinction between different types of novelty and the circumstances in which they arise should be considered and integrated in the NSM. We take this opportunity to expand the discussion on the subtypes of novelty and their possible different effects on curiosity and creativity.

We embrace **Jirout et al.**'s suggestion to look at novelty as a continuous concept, which implies that a certain level of novelty optimally drives the NSM. It is indeed reasonable to assume that there is an inverted U-shaped relationship between novelty and both curiosity and creativity. Whereby a moderate level of novelty may result in the optimal performance of the NSM, non-novel or overly novel information is less likely to result in effective recruitment of NSM. Building upon the involvement of dopaminergic activity in novelty detection (e.g., Duszkiewicz, McNamara, Takeuchi, & Genzel, 2019), studies showing a comparable relationship between dopamine levels and different types of cognitive processes (Cools & D'Esposito, 2011), including creative performance (Akbari Chermahini & Hommel, 2012; Boot, Baas, van Gaal, Cools, & De Dreu, 2017; Chermahini & Hommel, 2010), may partially support this hypothesis. For example, Gvirts et al. (2017) demonstrated how the effect of methylphenidate (which increases dopamine levels) on creativity was modulated by participants' level of novelty-seeking: Creative thinking in participants with low baseline levels of novelty-seeking was improved, while creative thinking in participants with high baseline levels of novelty-seeking was impaired.

The idea of novelty as a continuum was also raised by **Servais & Bastin** who suggested that prior knowledge determines novelty type and further modulates how novelty impacts memory. This relates to the distinction made by Duszkiewicz et al. (2019), and referred to in the target article, between *common* novelty (i.e., novel stimulation that shares similarities with relevant past experiences) and *distinct* novelty (i.e., completely new experiences that have minimal connections with past experiences), two ends with a continuous spectrum between them. Servais & Bastin further suggest that these novelty types are likely to tap into novel highly congruent and novel highly incongruent information (respectively). These two extremes are thought to be remembered better than less (in)congruent information (Quent, Greve, & Henson, 2022). This proposal, positioning novelty on a congruent–incongruent spectrum, may explain how novel stimulations may vary in their relative familiarity but still be attended to as novel (e.g., walking on the street and seeing a dog for the first time vs. seeing a specific breed for the first time such as Belgian shepherd).

Incongruency is further related to the surprise effect on memory, which for long was studied in isolation, but might contribute to the distinction between novelty types. **Becker et al.** call for a clear distinction between novelty, which relates to the unfamiliar, and surprise which relates to the unexpected. The commentators suggest that novelty signals which are triggered by unfamiliar stimuli and situations (either expected or unexpected) and surprise signals, which arise in the face of unexpected stimuli (either familiar or unfamiliar) are mathematically well-defined and may tap into different neural networks (we elaborate on the latter in the next section). We agree, and hope that examining the interplay between novelty and surprise in the future may elucidate different types of novelty. For example, Frank and Kafkas (2021) make a different distinction between expected novelty (stimulus) and unexpected novelty (contextual). *Stimulus* novelty refers to stimuli that have not been encountered before, and therefore are salient irrespective of expectation. *Contextual* novelty, on the other hand, relates to the unexpected pairing of familiar and novel inputs in a given context and is driven by expectation violation. These subtypes can be regarded as analogous to the common-distinct novelty continuum, while taking into account the viewer's expectations. Interestingly, according to Quent, Henson, and Greve (2021), the experience of novelty is never "absolute" in the sense that it cannot be defined independently of the observer; rather it is driven by the gap between what individuals expect to experience and what they actually encounter. This view challenges the idea of stimulus novelty that is independent from expectations, revealing the existing gap in our understanding of the different forms of novelty.

In sum, these different accounts highlight the need to unpack the concept of novelty, and delineate how the interplay between expectations and familiarity contribute to novelty. This interplay can be tested by embracing a design in which novelty is operationalized as stimulus novelty, and expectation is determined by the probability of occurrence within a set of stimuli (Frank & Kafkas, 2021). Future studies should further examine how this interplay affects curiosity and creativity. From a broader, theoretical point of view, it would be interesting to consider the mechanism supporting the prioritization of certain types of novelty for different subtypes of curiosity and creativity.

R2.1. Novelty-associated concepts

Beyond novelty, several alternatives that might drive curiosity, creativity, or both have been proposed by the commentaries. These include learning, uncertainty reduction, and familiarity, and we use this opportunity to broaden the discussion to include these related concepts.

R2.2. Uncertainty

The role of uncertainty in both curiosity and creativity is discussed in the target article in light of the SoM framework and is one of the possible links between the two. The question of whether uncertainty reduction not only links curiosity with creativity, but drives curiosity has been raised by several commentators. For example, **Holm & Schrater** assert that novelty is neither sufficient nor necessary to instill curiosity. They imply that non-novel, but uncertain situations may be enough to induce curiosity, giving as an example a specific case of specific curiosity (the urge to look up for the name of an actor while watching a movie). This example is akin to contextual novelty in which information is not novel, but is incongruent with the context, and as such, this example does not cover the diverse curiosity spectrum. Along similar lines, **Singh & Murayama** suggest that while creativity might be driven by novelty, curiosity drives people to seek information that reduces uncertainty (Fitzgibbon & Murayama, 2022; van Lieshout, de Lange, & Cools, 2021), rather than to seek the novel. This, too, explains a specific subset of curiosity-related behaviors which are directed towards the aim of filling an information gap, and does not account for all types of curiosity. Similarly, **Jirout et al.** claim that resolving uncertainty may be a better underlying basis for both curiosity and creativity than novelty-seeking. As suggested in the target article, curiosity may help transform situations of uncertainty from being experienced as threatening to providing a fruitful ground for the generation of novel ideas. This is quite similar to the commentators' approach explained elsewhere (Evans & Jirout, 2023), suggesting that one is curious when uncertainty is identified, and this uncertainty is responded to in a creative act.

These observations provide a clear example of how curiosity, and potentially subsequent creativity, is driven by the need to fill a gap. However, as clearly stated in the target article, not all creative acts or curious behaviors are driven by uncertainty reduction. Following Litman's (2008) distinction, we stated that the interest type of curiosity relates to the anticipated pleasure of new discoveries without benefiting from uncertainty reduction (e.g., curiosity about the movement of the clouds while looking at the sky), and only the deprivation type of curiosity is concerned with uncertainty reduction (e.g., understanding how an electrical device works so we will be able to fix it). Thus, we emphasize here again that while uncertainty seems to be linked with both curiosity and creativity, it does not necessarily drive all forms of curiosity and creativity. It is worth noting that in the target article we proposed that SoM determines which type of curiosity would be likely to be evoked, differentiating between deprivation and interest and clustering each with their governed SoM (and the associated subtypes of creativity). Further exploring how SoM, uncertainty, and novelty interact will be of pivotal importance for better understanding the contexts in which motivations for uncertainty reduction motivations shape novelty-seeking behaviors.

R2.3. Familiarity

People are often curious about the things they are familiar with. This is an excellent observation raised by **Singh & Murayama** and supported by studies showing that participants choose to learn about subjects they are already familiar with (Alexander, Kulikowich, & Schulze, 1994; Fastrich & Murayama, 2020; Tobias, 1994). While at first these findings might seem to contradict novelty-seeking, they can be explained by the common-distinct novelty spectrum discussed above. We can find novel information about topics that we are already knowledgeable about (or fill knowledge gaps, using the commentators' terminology). In a way, seeking novel information within a familiar context might be a formula for an optimal novelty level, which is not overly costly and at the same time highly learnable. For example, art lovers might get more curious about the opening of a new exhibition than gaining knowledge about other random subjects that they are not familiar with, similar to Tarantino's fans who will curiously anticipate his new film premiere while showing less curiosity about the release of a film by an unfamiliar director. The commentators claim that this knowledge gap (the exhibition or the film in this case) is likely to provide a bigger marginal gain to the audience in terms of understanding the topic; but they are nonetheless encoded as novel. In other words, familiar is not necessarily the opposite of novel. This is supported by novelty-detection theories according to which novelty and familiarity offer distinct contributions to recognition memory decisions, showing that their signals originate from non-overlapping brain regions (Kafkas & Montaldi, 2018).

R2.4. Learning

Omigie & Bhattacharya suggest a qualification of "novelty-seeking" as the pursuit of learnable novel information. They state that according to progress learning theories (e.g., Oudeyer, Kaplan, & Hafner, 2007), "curiosity is not solely driven by novelty but is precipitated by heightened rates of learning new information." Along similar lines, **Liquin & Lombrozo** further argue that expected learning and utility are primary to novelty, such that explicit signals of expected learning and utility are primary to triggering curiosity, compared with implied signals such as novel cues.

Indeed, learning plays a key role in driving curiosity, and we emphasize its importance in the NSM. We proposed that when we commit to the combination we generated in previous stages, it will result not only in consolidation, but with further learning and elaboration (p. 34). In other words, we agree that stimuli that have no learning potential will not be attended to in the first place or at most will fall in one of the subsequent stages of the model. That said, learning is not sufficient, it is the desired outcome but not necessarily the primary drive. Curiosity is driven by signals that are ultimately novel and meaningful. Similar to the interplay between usefulness and originality in creativity, an optimal balance between novelty and meaningfulness will result in consolidation and learning.

Omigie & Bhattacharya further postulate that curiosity limits wasting resources on irrelevant or overly simple content on the one hand, and on content that is too complex for our current understanding on the other. In other words, curiosity directs the agent toward moderately novel and learnable information. This is also explained by our model, and in line with the inverted U-shaped relationship mentioned above, whereby while we are attracted by novelty, not every novel stimulation will necessarily trigger our curiosity.

This discussion brings up the question of whether there is such a thing as *too novel*? For example, **Gustafsson et al.** claim that "an excess of novelty may be overstimulating, perceived as noise, and not necessarily evaluated positively." In our model, we proposed that the level of novelty is assessed during the multi-staged process of the NSM, and information that is too novel or that is insufficiently novel is more likely to be ignored, or later be ruled out. The same principle is true for creativity: Ideas that are not sufficiently original on the one hand, or overly bizarre on the other hand, will be ruled out and will not come to light. This is in line with the commentators who suggested reframing the need for novelty as a need for an optimal level of arousal (in which exploratory behaviors are used to maintain the arousal level). Both cases highlight the need for moderate-level novelty as a drive for creativity and curiosity. That said, future studies in both the curiosity and creativity realms are needed to examine this premise more thoroughly.

Furthermore, the notion that novelty-seeking can be rather costly, was raised by several commentators (e.g., **Gustafsson et al.**; **Omigie & Bhattacharya**), and we indeed agree that too much novelty-seeking can be unadaptive. By further addressing the subtypes of novelty, we were able to better allude to the costs of novelty in our model. As pointed out by **Zhou & Berenstein**, the desire to explore and learn novel information must thus be balanced in order to avoid an overflow of information. As indicated by the commentators, one way to manage this is to use heuristics that locally track what has and has not been seen before. By contrast, familiarity may be used to reduce uncertainty and acquire missing information. While the latter can be seen as a form of perseverative information-seeking and has been associated with deprivation curiosity, the former might be linked to diversive curiosity. This is in line with the SoM framework and with the suggested matrix that we composed, according to which hyper-exploration will result in an overflow of information while hyper-exploitation will result in a stand-still perseverative state. In either case, if not balanced, both can result in dysfunction. Extreme preference for familiarity is prevalent in depression and anxiety, while attraction to excessive novelty might be associated with hypomania and psychosis (e.g., Baas, Nijstad, Koen, Boot, & de Dreu, 2020).

On a related note, **Kashdan et al.** point to the possible costs creativity and curiosity hold (metabolic, psychological, social), which when maximized may produce overstimulation due to vigilance and may result in dysfunction. Similar to an optimal level of novelty or arousal, optimal level of curiosity and creativity balances their costs and benefits based on contextual demands. In line with the matrix suggested in the target article and with the inverted U-shaped function, too little or too much creativity or curiosity may result in negative outcomes to the point of psychopathology.

To conclude, in the target article, we referred to novelty in a very general manner to be able to construct a unified and parsimonious model that explains the commonalities between different novelty-seeking behaviors (e.g., curiosity and creativity). Based on the commentaries cited above, here we decomposed novelty, taking into account potent features (expectations and familiarity), and examined the different subtypes of novelty resulting from the interplay between these concepts. By doing so we show that although several variables interact in the process of curiosity and creativity, as alluded to in the target article, novelty-seeking best explains the underlying basis of human curiosity and creativity. Interestingly, our assumption is supported by recent computational evidence showing that when exploring complex environments, novelty-seeking is the most probable model of human behavior, outperforming seeking information-gain or surprise (Modirshanechi, Becker, Brea, & Gerstner, 2023). We encourage future research to empirically test whether different types of novelty commonly guide curiosity and creativity.

R3. Subsystems and possible mechanisms

In the target article, we pointed out possible neural systems that subserve the NSM. However, as neural evidence is still lacking, how novelty is processed in the human brain, and the specific neurochemical systems involved are still elusive. We therefore embraced a more theoretical approach and avoided overly speculative mechanistic explanations, while noting that the networks and mechanisms suggested are not solely involved in curiosity and creativity, a concern that was raised by some of the commentaries. This is a challenge neuroscience often faces when attempting to assign a unique function to a specific cortical region or network. A more mechanistic approach is certainly needed to advance our understanding of the possible link between curiosity and creativity, which will be increasingly possible with more research. Our model provides a basis for future investigations to suggest the involvement of potential mechanisms, as some of the commentaries also attempted to do (e.g., **Servais & Bastin**; **Chiou et al.**; **Zeitlen et al.**; **Faber & de Rooij**; **Prasad & Hommel**). These are important additions, and we discuss them in more detail below.

R3.1. The interplay between episodic and semantic memory

A great part of the discussion in the target article on the role of memory in creativity and curiosity was dedicated to semantic memory (although the role of episodic memory was briefly alluded to, e.g., Duszkiewicz et al., 2019; Madore, Addis, & Schacter, 2015, 2019). This is mainly due to the fact that the bulk of evidence reviewed by us investigated semantic memory as the main system involved in both. However, we acknowledge that understanding the role of episodic memory in creativity and curiosity will certainly shed more light on their common basis.

Interestingly, the interplay between these two memory systems is closely related to novelty detection and may tap into the possible subtypes discussed above. **Servais & Bastin** point out that the distinct subtypes of novelty lead to memory representations of different nature. In *common* novelty, new information that is congruent with prior knowledge will be combined with prior semantic knowledge to fill an existing gap within the associative semantic network. On the other hand, *distinct* novelty is thought to form episodic, standalone memories. The commentators further hypothesize that the two ends of the U-shape are linked to different memory systems: While congruent information is supposed to be stored as semantic representations, incongruent information is thought to induce episodic memories. Although appealing, this assumption may be true in limited cases, as encoding of episodic experiences can be schema-congruent at times. Moreover, the view of semantic and episodic memory as functionally distinct is gradually replaced by seeing them as complementary and interrelated memory systems (Benedek, Beaty, Schacter, & Kenett, 2023). Future studies should consider in more depth their complementary contribution to both creativity and curiosity. Given the view of interdependency between semantic and episodic memories, such investigations are likely to result in a more intertwined mechanistic structure than a parallel dual-paths model.

R3.2. Subsystems of DMN/ECN

In accordance with the involvement of episodic and semantic memory, **Choui et al.** suggest that both the DMN and ECN are functionally fractionated into subnetworks, which potentially enables distinct facets of creativity (and curiosity). According to their proposal, there is a dissociation between a "semantically oriented subnetwork," which is associated with semantic memories, evaluative cognition, and convergent thinking, and an "episodically oriented subnetwork," which is more associated with episodic memories, free association, simulating hypothetical scenarios, and divergent thinking. Their suggestion accords with the distinct roles of memory systems discussed above and provides an initial framework for the differences between creativity induced by semantic and episodic memories, and the distinct subsystems involved in each case.

Another important issue related to the heterogeneity of those networks was raised by **Benedek** who commented about the interaction of the DMN and ECN with various processes–stages in the NSM. For example, DMN structures also contribute to idea evaluation (Benedek et al., 2023), and cognitive control is also involved in idea generation (Benedek & Jauk, 2019). While we only schematically associate neural networks with specific stages along the model, based on previous evidence, we agree that their contribution is likely to go beyond a single, specific stage. This may be valid also for **Prasad & Hommel**'s assertion that attention is implicated in all four stages and not only in the affinity stage, or that of **Gabora et al.**, who interpreted the model as composed by distinct rather than interweaved phases. In the target article, we alluded to these dynamic interplays between the networks and between the stages (such as the cyclic motion between evaluative and generative processes), but we agree that the dynamic sub-interactions *within* the systems as postulated by **Chiou et al.** may promote a more refined understanding of the mechanisms involved throughout the process.

Considering these dynamic sub-interactions may further explain the potentially differential neurochemical effects on the distinct subtypes of creativity and curiosity. Although beyond the scope of the target article, this is a valid assumption that should be tested, as mentioned by **Baas et al.**, suggesting that these differential effects ultimately feed into creative thinking and doing (Beversdorf, 2019; De Dreu, Nijstad, & Baas, 2024). Other than the involvement of dopamine, which we describe in the target article, surges in norepinephrine among others may be involved in novelty as we discuss next.

R3.3. The role of the noradrenergic system/dynamic threshold

In light of the interesting commentary by **Faber & de Rooij**, we discuss here the possible role of the noradrenergic system in the NSM.

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Based on the adaptive gain theory (Aston-Jones & Cohen, 2005), which proposes that locus coeruleus norepinephrine (LC-NE) serves to adjudicate the trade-off between exploration and exploitation, the commentators suggest that the activation threshold, described in our model, may be adaptive to contextual demands. For example, the threshold may be more selective (higher) when one is stuck, looking for a tailored solution for a specific problem, and this threshold is adaptively lowered during incubation, allowing for more ideas to attract our attention so progress can be made.

The adaptive gain theory is of great relevance, originally suggesting that exploitatory mode is driven by phasic norepinephrine (NE) for prioritizing related information and tonic NE is associated with an exploratory mode promoting search for other alternative behaviors. Upshift in tonic NE enhances functional connectivity in relevant networks and reduces phasic responses to the extent that attentional decoupling occurs, which facilitates a more exploratory mode. As further highlighted by the commentators, while moderately heightened tonic NE, which increases sensitivity to novel information, may facilitate creativity through defocusing; phasic NE enhances response to salient events and thus helps in the selection of the ideas that will cross the threshold. These dynamics shed more light on the possible role of NE in novelty-seeking and are in line with the readiness potential, described in the target article as the driving mechanism for novelty detection (see Broday-Dvir & Malach, 2021, for detailed description). During this slow uprising phase of spontaneous fluctuations in cortico-hippocampal circuits, a spontaneous mental event can emerge. This is followed by low-level activation spread in relevant networks generated by any new content (Noy et al., 2015) and ends with dopamine release in the hippocampus. This bodes well with the adaptive gain theory that proposes that these systems work in synergy: The LC-NE system regulates the balance between exploitation and exploration, and the new knowledge is implemented and rewarded by the DA system (Aston-Jones & Cohen, 2005).

Faber & de Rooij further suggest that the adaptive gain theory may explain how saliency is affected by changing environmental demands. As an example, the commentators postulate that in response to an impasse, this upshift in tonic NE might reduce the bias to previous neural activity that has led to the impasse and lower the novelty threshold accordingly, raising the chances for more spontaneous ideas to become salient. However, as a lowered threshold might come at the cost of accuracy, when overcoming the impasse, the threshold is adaptively raised, through more deliberate modes of creative thought. Although the commentators propose how incubation "resets" the threshold through attentional decoupling, allowing for spontaneous ideas to emerge from subsequent mind wandering; this mechanism may possibly explain the interplay between spontaneous and deliberate processes in a broader sense. Our suggestion that the activation phase is mediated by the salience network is supported by the adaptive gain theory, proposing that the anterior cingulate cortex (ACC), a key region in the salience network (SN), regulates the transitions between phasic and tonic NE. While future research is yet to determine the role of the noradrenergic system in curiosity and creativity, understanding the adaptivity of the activation threshold to contextual constraints is of great importance.

R3.4. Metacontrol

The expanded discussion here about the possible neurochemical mechanisms involved in balancing the trade-off between exploration and exploitation may provide a mechanistic, cognitive-control related element that is lacking in the target article, as suggested by **Prasad & Hommel**. The commentators highlight the importance of cognitive control in balancing opposing forces or control strategies by switching from top-down to bottom-up states of processing. This idea shares significant commonalities with the description of exploration as derived from bottom-up processing and exploitation from top-down control, as shown in the target article and explained originally and in detail by the SoM framework (Herz, Baror, & Bar, 2020). We hope that the expanded discussion here about the possible neurochemical mechanisms involved in the balancing trade-off between exploration and exploitation adds clarity.

Furthermore, in line with the contributions of the metacontrol model (Hommel, 2015) or of reinforcement models such as those of **Becker et al.**, we encourage future studies to quantify the respective contributions of exploration and exploitation to the NSM and test which mechanisms regulate the trade-off between exploratory and exploitatory states. We also accept **Arbib**'s notion, by which the SoM framework didn't elaborate how exploration and exploitation relate to the DMN, SN, or ECN. With this gap, it would be important that future investigations examine how interactions within DMN–SN–ECN are influenced by one's SoM on the exploration–exploitation continuum, and whether in accordance, these mechanistic interactions are represented in the different subtypes of curiosity and creativity.

Lastly, **Baas et al.** point out that the role of neural oscillations captured by EEG is ignored in the NSM. Although there is a growing body of evidence regarding the role of alpha power in creativity, as the commentators propose, EEG studies of curiosity are lacking (but see Appriou et al., 2020). We agree with the commentators that a combination of different neuroscience methods will ultimately reveal the unified nature of curiosity and creativity and thus invite future studies to examine their neural basis via varied methods.

R3.5. Mood

Some commentaries emphasized the possibility that mood regulation might serve as a shared mechanism to promote creativity and curiosity. Although only briefly mentioned in the target article, according to the SoM framework (Herz et al., 2020), affect is a major pillar of SoM, together with dimensions such as perception, attention, thinking, and openness to experience (i.e., the exploration–exploitation continuum). Whereas broad SoM is associated with positive mood, with creativity and with exploratory behavior, narrow SoM is associated with negative mood, a constricted thinking pattern and exploitatory behavior.

Zeitlen et al. support the reciprocal connection between curiosity and creativity by suggesting how both are commonly driven by the desire to enhance positive moods and/or reduce negative moods. In line with their proposal and with the SoM framework, specific curiosity and convergent thinking are associated with negative mood reduction, and diverse curiosity and divergent thinking with enhancement of positive mood (see also Bar, 2009). The suggestion that curiosity and creativity are purposeful vehicles for mood regulation is an appealing avenue for future research.

Zeitlen et al. further suggest that the link between curiosity and creativity goes beyond mood regulation, in which mood can promote information-seeking by increasing the perceived value of information. In the same vein, **Gustafsson et al.** suggest that mood changes one's cognitive resources and arousal levels of the stimuli met in a given context. A stimulus must have a potential positive reward to trigger the intrinsic motivation to explore. The reward is context-dependent such that a very simple stimulus, usually perceived as boring, could be positively rewarding if one is under-stimulated. It is important to consider, however, cases of morbid curiosity (as raised by **Baas et al.**), in which we may be curious about negative information. This negative information, however, may be assigned with positive value, driving one's curiosity and will result in new rewarding knowledge. In the same manner, this may explain cases of dark or malevolent creativity, in which novel ideas aimed at damaging others (Perchtold-Stefan, Fink, Rominger, & Papousek, 2022).

Furthermore, **Zeitlen et al.** states that the unified process underlying creativity and curiosity is flexibly affected by mood: "positive mood typically promotes an exploratory SoM, fostering creativity and diversive curiosity; but when a local style is dominant in one's SoM, then negative mood promotes an exploratory SoM and positive mood might promote an exploitatory SoM, fostering specific curiosity." This is perfectly echoing our premise in the target article, and in more detail in Herz et al. (2020) and Bar (2009). Indeed, mood reinforces processing style, as embedded by SoM, and is directly influenced by the current context. We further suggest that both exploitatory and exploratory SoMs may result in creativity/curiosity (novelty-seeking), but of different types. This framework adds a more nuanced approach to understanding motivational and contextual conditions in which curiosity and creativity may flourish.

R3.6. Developmental perspective

The NSM could be applied across the lifespan, as suggested by **Vaisarova & Lucca**. The commentators point to evidence showing that children do not show greater ideational fluency, as might be predicted by our model. As an example, they assert that there is a negative correlation between fluency and executive functions in kids, as opposed to adults. The latter is of interest as the commentators further suggest that there might be a qualitative change in top-down processing across age. In line with the cyclic motion between generative and evaluative processes and the evidence that regions in the ECN are activated during generation of ideas, it is possible that the interplay between the processes changes with age. Indeed, studies demonstrate that adults show stronger functional connectivity between and within the DMN and ECN up to adulthood (Fair et al., 2008; Sherman et al., 2014; Uddin, Supekar, Ryali, & Menon, 2011), and more specifically an increased SN influence, which guides the switching between those networks, was found across development (Uddin et al., 2011). Similar findings were evident during a divergent thinking task, where older adults showed stronger functional coupling between the DMN and ECN compared with young adults, implying that greater default-executive functional coupling occurs with age (Adnan, Beaty, Silvia, Spreng, & Turner, 2019). These dynamics might be affected by the social context as further suggested by the commentators and supported by studies who found that cultural (Ivancovsky, Kleinmintz, Lee, Kurman, & Shamay-Tsoory, 2018), school-experience (Duval et al., 2023), and expertise (Kleinmintz, Goldstein, Mayseless, Abecasis, & Shamay-Tsoory, 2014) may modulate these brain networks in creative thinking.

Similarly, children may be less successful in governing the trade-off between exploration–exploitation and switch between these strategies throughout the process. While children are exploratory in nature, utilizing the advantages of exploitatory behavior may increase across development with the gradual maturation of their prefrontal cortex and the acquisition of experience. Furthermore, adults' exploratory behaviors, such as curiosity and creativity, may inherently require exploitation abilities (e.g., inventing a useful tool; see Neldner et al., 2019) and rely less on "pure" exploration as children (see Gopnik, 2020, for a more elaborated discussion). It is thus possible that in accordance with the discussed subtypes of novelty, children will experience more *stimulus* novelty, as indeed more experiences are truly novel for them, and will gradually switch to *contextual* novelty in adulthood.

Considering developmental changes in the concept of novelty would be an interesting perspective for future investigations. For example, a recent developmental study found that whereas adolescents and adults demonstrate attenuated uncertainty aversion for more novel choice options, children's choices were not influenced by reward uncertainty when choosing options that entail greater novelty (Nussenbaum et al., 2023). Developmental accounts are therefore of great importance for a more comprehensive understanding of novelty-seeking, curiosity, and creativity.

R4. Different pathways lead to different CC subtypes

In the target article, we proposed a generalized model to describe and connect curiosity and creativity. After substantiating the model, we then described the subtypes of both curiosity and creativity and suggested possible interactions between these subtypes and the SoM framework, resulting in two endpoints of a continuum, one more associated with exploration and the other with exploitation. It is possible that those clustered subtypes are interconnected by different cognitive pathways, associated with distinct neural subsystems, as implied by some of the commentaries. Alternatively, alterations between these two yet-hypothetical pathways throughout the NSM may be necessary to optimize performance based on context and the available resources. In line with the SoM framework, we suggested that these shifts throughout the NSM are determined by the balance between top-down (TD) and bottom-up (BU) processing (Herz et al., 2020). Future research is yet to determine whether these clusters represent two separate cortical infrastructures or are associated with the same infrastructure, but with varying weights that give an advantage to TD or BD processing. As empirical evidence that links curiosity and creativity is still lacking, our model sets the ground for such investigations.

R4.1. The role of usefulness

Utility is an important aspect of every human behavior, and its role in curiosity and creativity has been rightfully emphasized by the commentators (**Acar & Fuchs**; **Liquin & Lombrozo**; **Litovsky et al.**; **Runco**). Considering that creativity requires both novelty and usefulness (Runco & Acar, 2012; Sternberg & Lubart, 1996), and that curiosity is rewarded by new knowledge (i.e., learning) and novel experiences (Kashdan & Silvia, 2009; Litman & Jimerson, 2004), utility potentially plays an important part in both. As further suggested in the target article, novelty should be accompanied by usefulness for avoiding bizarre or useless/esoteric ideas or information. This balance is achieved through iterations between the affinity phase, where novelty is prioritized, and the evaluation phase in which other valuation

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components are taken into consideration, such as usefulness and appropriateness. The balance between the two is further governed by SoM; in exploratory SoM, we prioritize novelty and diversity, and in exploitatory SoM, we lean toward immediate utility (e.g., filling a knowledge gap, finding a solution to an existing problem/elaborating on an existing idea). Indeed, utility has been suggested to influence exploration–exploitation tendencies: When high utility is predicted by prior events, exploitation is enhanced, and if low utility is predicted, exploration of novelty emerges (Aston-Jones & Cohen, 2005; Cohen, McClure, & Yu, 2007).

As research on usefulness is somewhat of a later contribution to the work on creativity, the relationship between usefulness and originality is disputed (Harvey & Berry, 2023). **Acar & Fuchs** underscore the distinction between novelty and usefulness, suggesting that these two components might be independent of each other. **Runco** points to the possibility that novelty and usefulness are simultaneously processed. While Acar & Fuchs are concerned by the (over) interdependency between usefulness and originality suggested in the target article, and Runco's concern is the complete opposite, holding that usefulness and originality are presented in the model in clear separation. These conflicted readings clearly reflect the debate in literature. Relying on dual models of creativity (e.g., Basadur, 1995; Sowden, Pringle, & Gabora, 2015), we proposed that novelty and usefulness are balanced throughout a cyclic motion and iterations between generative and evaluative processes, implying their interrelated nature. Although we describe them as sequential in our model, whereby affinity is triggered by novelty and only then assessed for its usefulness, we do not see them as isolated processes, as implied by Runco, but rather as two critical parts within a more comprehensive process.

Runco makes an important observation that usefulness changes from one domain to the other. In the same vein, social and cultural factors may influence the balance between originality and usefulness in creativity, favoring one or the other (e.g., Erez & Nouri, 2010; Ivancovsky, Shamay-Tsoory, Lee, Morio, & Kurman, 2021). This is in line with **Vaisarova & Lucca**'s developmental perspective suggesting that "social cues may draw individuals' attention to certain aspects of their environment, as well as shaping their goals and evaluation criteria. Standards for the usefulness of an idea, for instance, might be higher in a context where it will be used by others."

Liquin & Lombrozo argue that in curiosity, utility is primary to novelty and that curiosity is sensitive to novelty mainly because it signals that useful learning is likely. They support their assertion by demonstrating how sensitivity to utility triggers is likely to produce "optimal" patterns of curiosity: High curiosity when useful learning is most likely and most rapid, and low curiosity when useful learning is least likely and least rapid (Liquin, Callaway, & Lombrozo, 2020, 2021; Poli, Serino, Mars, & Hunnius, 2020). This pattern of results can similarly reflect the balance between novelty and usefulness, explaining why *too-novel* information that completely lacks usefulness is less likely to be consolidated. While the priority of novelty and usefulness in curiosity may be debatable, considering the interplay between them, as suggested in the target article and discussed in further detail here may hold a key function.

On the contrary to the commentaries discussed above, **Litovsky et al.** criticize the inclusion of utility whatsoever, stating that the model fails to explain why non-instrumental information is attended to (e.g., gossip), or why valuable information is sometimes ignored. **Acar & Fuchs** further suggest that novelty-seeking might be unrelated to usefulness, proposing that curiosity may lead to prioritizing novelty over usefulness, referring to studies that found that curiosity and interest are crucial for the initial phase of the creative process (Amabile, 1996), and that individuals with a strong motivation to acquire new knowledge generate less useful solutions to innovation problems (Acar, 2019). These examples are in line with our suggestion that the subtypes of curiosity and creativity may be interconnected in a distinct way: While originality is linked to interest or diversive curiosity and divergent thinking, usefulness may be linked to specific curiosity and convergent thinking.

Interestingly, Dubey, Griffiths, and Lombrozo (2022) suggest that curiosity may arise for information that may seem initially unimportant – if people come to appreciate its usefulness. **Litovsky et al.** claim that other theories, such as the information gap theory (Loewenstein, 1994), can predict when curiosity will be piqued, but link this claim uniquely to specific/deprivation curiosity, thus, do not explain other forms of curiosity. Furthermore, studies show that uncertainty reduction, associated with this type of curiosity, is also guided by utility. As **Liquin & Lombrazo** suggest, people aren't curious about all uncertain stimuli (i.e., information gaps), but specifically those likely to be useful in the future (Dubey & Griffiths, 2020; Dubey et al., 2022). If this is the case, the question that Litovsky et al. raise still remains. Information gaps are part of our enriched environment, as we cannot attend them all, some are prioritized based on their novelty, utility, and individual differences.

Why people avoid useful information and choose not to resolve their information gaps, even if it is optimal to do so, remains a question for future research. As **Horton & Mason** acknowledge, we understand relatively little about the circumstances that prompt an individual to innovate or to attend to novel information rather than settle for a standard or routinized approach. Our model sets the ground for identifying the conditions under which people self-initiate curious or creative pursuits.

R4.2. Persistence versus flexibility

The SoM framework discussed in the target article highlights the tension between exploration and exploitation, and their corresponding function in novelty-seeking behaviors. This tradeoff is reiterated in the commentary made by **Baas et al.**, who elaborate on two cognitive pathways (De Dreu, Baas, & Nijstad, 2008): *Flexibility* in which original ideas are generated by switching between broad cognitive categories, and *persistence* in which equally original ideas are generated through a systematic exploration of a semantic category in-depth, evaluating and discarding more readily available ideas. These parallel the broad and narrow SoMs introduced in Herz et al., 2020. While the flexibility pathway is linked with curiosity, novelty-seeking, openness to experience, positive mood, and desirable outcomes, persistence is associated with working memory capacity, negative mood, and threatening circumstances and may result in morbid curiosity and dark creativity. Bringing these ideas together, we identify that flexibility is key to exploration and persistence is analogous to exploitation. These similarities are also acknowledged by **Benedek**, who ingeniously listed most complementary or opposing concepts mentioned by us and others, using different labels for largely the same thing. We hope that using converged terminology may advance future interdisciplinary discourse.

As further mentioned by the commentators, the balance between flexibility and persistence helps avoiding distractibility and bizarre ideas on the one hand (too much flexibility) or rigidity on the other (too much persistence), similar to the dynamic interplay between exploration–exploitation and cognitive control suggested by us. This interplay may also be addressed by the usefulness–originality continuum perspective. As succinctly summarized by **Prasad & Hommel**, behavior requires balancing two extremes, and integrating the situational constraints with personal goals. We believe that similar to originality and usefulness, persistence and flexibility mirrors the exploration–exploitation balance, and although it has been claimed that the exploration–exploitation distinction does not gain added value from the SoM framework (**Arbib**), we do believe that clustering the extreme ends along different dimensions under an overarching framework is beneficial in explaining how all those continuums change in tandem, and how various forms of creativity and curiosity interact. In this sense, **Moldoveanu**'s exploratory exploitation and exploitative exploration concepts are intriguing. It is possible that exploration and exploitation are weaved in a more complex or intermixed manner, but more evidence that pinpoints these subtypes of connections is needed to support such hypotheses.

Interestingly, **Horton & Mason** indeed call for a deeper dive into how various forms of curiosity and creativity are related. They suggest that considering the multiple pathways in which curiosity might affect creativity may offer a more comprehensive approach. For example, they propose a nuanced and elegant distinction between *depth-curiosity* and *breadth-curiosity* to clarify their corresponding contribution to creativity. Depth-curiosity is analogous to the specific/deprivation type, and breadth-curiosity is analogous to the interest/diversive type. These semantic labels used by the commentators may help portray the distinction between these subtypes more accurately. Second, adopting these labels may better demonstrate the relationship with the different creativity subtypes and with the SoM framework as depicted in our model, which may further illuminate how exploration and exploitation interact. Horton & Mason add support by suggesting that depth curiosity may lead to the development of expertise and enhanced problem-solving skills (Harrison, Sluss, & Ashforth, 2011; Lydon-Staley, Zhou, Blevins, Zurn, & Bassett, 2021; Zhou, Xiao, & Zhang, 2020), while breadth curiosity may be instrumental in making remote associations. This is in line with our suggestion that diverse curiosity is closely related to divergent thinking, while specific curiosity is associated with convergent thinking. Depth and breadth curiosity further tap into the persistence (in-depth exploration) and flexibility (switching between broad categories) pathways. Although using slightly different terminology in our model, we acknowledge the great contribution of the pathways approach to the future establishment of a unified but nuanced model of curiosity and creativity.

R5. Creativity and curiosity "in the wild"

Although beyond the scope of the target article, understanding real-life curiosity and creativity is of importance but *typically less investigated*. According to **Omigie & Bhattacharya**, creativity and curiosity in areas such as art, music, and poetry is driven by learnable novelty. As an example, they cite Bianco, Ptasczynski, and Omigie, 2020; Cheung et al., 2019; Omigie and Ricci, 2023, demonstrating that learning a new musical style (i.e., the outcome of being curious) significantly predicted success in composing creatively in that new style. They further cite as an example Zioga, Harrison, Pearce, Bhattacharya, and Di Bernardi Luft (2020) who found that musical compositions with moderate, rather than high levels of novelty (i.e., music intervals not previously heard), were judged by listeners as being the most creative. This interesting finding demonstrates how our suggested inverted U-shaped function of optimal novelty levels extrapolates to real-life creativity.

Another example that **Omigie & Bhattacharya** give to support the learning–creativity link is that aesthetic appeal is a stronger predictor than surprise of how creative poems are judged to be (Chaudhuri, Dooley, Johnson, Beaty, & Bhattacharya, 2023). According to the NSM, the novel stimulation is evaluated based on different criteria including the relevance of the content to the context. Aesthetic appeal may relate to the usefulness component in art rather than to mere learning–creativity associations as suggested by the commentators. This is also in accordance with **Runco**'s suggestion that usefulness in art is portrayed by aesthetic usefulness, rather than practical function or norms.

We join the commentators in stressing the need for research on curiosity and creativity to go out of the lab and investigate real-life creative behaviors. Under such circumstances, a broader set of motivations may come into play, as well as one's commitment to the creative outcome, as is the case for players and artists. This insight is reflected in a commentary by **Pagnini et al.**, who propose that mindfulness is a necessary condition for both curiosity (novelty-seeking) and creativity (novelty-producing), indicating that both factors are typically highly correlated. The commentators interestingly suggest that rigid thinking patterns when mindless prevent curiosity and creativity. When mindful, people are open to novelty, pay attention to the variability of the experience, and adopt multiple experiences, which all facilitate curiosity and creativity. One's level of intention and mindfulness is likely to change in out-of-lab settings, and this element should be taken into consideration.

Moreover, while we mainly focused our discussion on lab-based experiments of creativity, which heavily rely on semantic or linguistic knowledge and problem solving, real-life creativity, such as sculpting, design, or cooking, involves more domains than that. An interesting question that applies to both curiosity and creativity, and was briefly mentioned when discussing familiarity, is the question of domain-specificity. Artistic creativity involves visual, procedural, improvisational skills among others. Yet are curiosity and creativity domain-specific or domain-general? **Arbib** depicts in his commentary the case of architecture and design creativity and describes in similar terms how architects navigate their own mind (or locometric maps) to turn scripts into buildings. It is likely that mental simulation, guided by the relevant knowledge structure, is one such common process. Future studies are yet to determine whether creative ideation shares similar memory processes across domains (see Benedek et al., 2023).

In the context of "real-life," **Servais & Bastin** suggests that the NSM could also address the case of brain-damaged patients with memory problems and the fact that they present decreased creativity (Duff, Kurczek, Rubin, Cohen, & Tranel, 2013). Interestingly, as mentioned in the target article, several lesion studies and case studies on FTD patients (fronto-temporal dementia) among others showed enhanced artistic creativity abilities (see Geser et al., 2021, for a review). These findings may be also relevant for the domain-specific/general discussion above as patients might show dissociation among enhanced and decreased creative abilities. To the best of our knowledge, there are no studies investigating curiosity among brain-damaged patients, but this may be an important future research line to shed more light on

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the neural underpinnings of both. For example, does curiosity remain intact among patients with memory problems? Would curiosity inductions help mitigate impairments to memory functioning? As some evidence shows that curiosity (and novelty-seeking in general) may have lifelong benefits for memory abilities by affecting hippocampal performance and structure (see Sakai et al., 2018, for a review), it may be the case that a form of curiosity-training may aid memory deficits.

R6. Linking curiosity and creativity

Finally, questions regarding the nature of the mutual connections between curiosity and creativity were raised by some of the commentaries (e.g., **Becker & Cabeza**; **Zhou & Bornstein**; **Karwowski & Zielińska**; **Grüning & Krueger**; **Singh & Murayama**). As **Benedek** points out, in the target article, we performed a "mental factor analysis" on the correlates of creativity and curiosity to extract the factor explaining the most shared variance. We are happy to witness a growing body of research linking curiosity and creativity published since we first submitted our target article (e.g., Evans & Jirout, 2023; Kenett, Humphries, & Chatterjee, 2023; Li, Emin, Zhou, Zhang, & Hu, 2023). In the discussion below, we focus on the issue of causality and on what could be claimed and safely suggested with the current state of research.

Singh & Murayama claim that curiosity and creativity differ in their basic motivation: While people are curious about knowledge gaps between closely related concepts, creativity requires the ability to connect semantically distant concepts. As stated by the commentators, according to the knowledge network theory "… people often feel curious when they perceive the potential for adding new edges between semantically close concept nodes," while "creativity motivates people to take substantial semantic leaps away from the current stimuli and connect the pieces of information that were far apart." Although the commentators provide it as an example of the differences between the two, we believe that this aspect is what brings them together. The more interlinked nodes in one's associative network, the easier it would be to make those leaps and connect remote concepts. As suggested in the target article, this notion that "consolidation of interlinks in memory, as curiosity seems to promote, would enable connecting nodes in a novel manner and the shortening of path lengths in the network" (p. 14) is supported by network-science studies showing that increased interconnectivity between concepts tend to characterize associative networks of creative thinkers (Benedek et al., 2017; Gray et al., 2019; Kenett, Anaki, & Faust, 2014).

Interestingly, as proposed by **Zhou & Bornstein**, curiosity and creativity may both be linked with a form of mental navigation through complex knowledge structures that span diverse spaces. That knowledge may be more modular and compressible, allowing for the grouped representation of a more diverse chain of actions. According to their computational approach, while curiosity expands one's knowledge, creativity compresses existing knowledge by chunking or recombining information, thus managing the cost of increased complexity. These computational processes can be seen in the same vein as expansion of interlinks and shortened paths as described above, supported by studies that found that associative networks of high creative individuals are more condensed, as more concepts are clustered and less rigid than low creative individuals (Kenett et al., 2014; Kenett & Austerweil, 2016; Li, Kenett, Hu, & Beaty, 2021). The commentators mention that the DMN contains the most compressed neural activity that has been measured, which again supports this notion.

Becker & Cabeza suggest that curiosity and creativity share the same underlying computational principle of prediction error minimization. While curiosity corresponds to an expected gain of novel information, creativity (or more specifically the AHA experience) corresponds to the actual gain of novel information. In other words, while in curiosity the model is updated based on future expected gain for the novel information acquired, in creativity the model is updated with a known gain of novel information that was generated, providing the agent a sense of certainty. Future research is yet to determine whether uncertainty reduction and accurate representation of the world is one of the functions that creativity may (or may not, according to **Singh & Murayama**) serve. However, it is important to consider the prediction error minimization idea when approaching the debate. In accordance with **Zhou & Bornstein**, creativity may increase certainty and support the pursuit of long-term goals, because once a problem is solved, the uncertainty associated with this problem is reduced. In other words, at least the convergent subtype of creativity involved in problem-solving may serve to reduce uncertainty, similar to the deprivation subtype in curiosity. This link is also supported by **Gustafsson et al.**'s optimal arousal model according to which both specific curiosity and convergent thinking are aimed at solving problems to simplify one's environment. However, diversive curiosity and divergent thinking are aimed to get more stimulation and to complexify one's environment and thus may not be associated with uncertainty reduction. This debate is likely to unfold by future work that would investigate whether uncertainty reduction is nonetheless driving all forms of creative and curious behaviors.

Another perspective was offered by **Grüning & Krueger** who propose that creativity moderates whether curious people can engage in information-seeking behavior. This goes beyond our identification of a link between curiosity and creativity and advances to suggest a causal relationship between the two. According to their model, a certain degree of a certain type of curiosity and creativity is prerequisite for exhibiting information-seeking behavior and eventually the two suggested pathways of "information-generating" and "information-gathering" result with the same behavior. This idea is interesting and requires more elaboration and evidence. What are the qualitative differences between these two pathways in terms of outcome? Why does "information-generating" relate to specific curiosity more than diverse curiosity? These open questions are yet to be answered before an unequivocal causal link between creativity and curiosity can be made.

On that note we should emphasize that our proposed NSM does not dismiss other possible variables that might link curiosity and creativity, which seems to have been the concern of several commentators (**Litovsky et al.**; **Holm & Schrater**; **Runco**). We rather provide a novel approach for investigating the proposed link between them. The host of findings we have cited in the target article, together with those provided by the many supportive commentaries, indicate a strong case for why this framework should be pursued and thoroughly tested in the future. We hope that by advancing the theoretical understanding about the link between curiosity and creativity and establishing a testable model, we set the ground for empirical research to elucidate their intuitive yet complex relationship (a challenging mission, as evidenced in **Raz & Kennet** commentary). Unified definitions and reliable measures of each of the subtypes of curiosity and creativity are necessary to achieve this important goal.

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