Curiosity and the regulation of affective memory

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Abstract

We propose a cognitive and neurobiological model by which curiosity aids emotion regulation through abstract and flexible information-processing, which may positively bias memory. We begin with an overview of curiosity's emotional effects. Then we introduce models of affective memory encoding to suggest that the dopaminergic modulation of encoding associated with curiosity may positively bias these processes. Next, we identify how neural processes underlying curiosity in the left inferior frontal gyrus (LIFG), the dorsal anterior cingulate cortex (dACC), and the lateral prefrontal cortex (LPFC) address mechanisms underlying our framework. Specifically, we argue that curiosity's regulatory mechanisms of abstraction and cognitive flexibility, in combination with its memory mechanisms, predict that curiosity is likely to encode arousing information through positively biased neurobiological pathways.

Keywords: Curiosity, Affective Memory, Emotion Regulation

Introduction

In Lewis Carroll's famous story "Alice in Wonderland", we are introduced to a character who is literally dropped into the middle of a world filled with uncertainty and threats. And yet, Alice, and the children reading her story, are able to navigate the world without fear, but rather with eyes wide open with interest. "Curiouser and curiouser" remarks Alice, early on in the text, and perhaps in this comment the reader begins to understand both how Alice is going to persist and how we are meant to engage with the story. Rather than perceiving the oddities of this new world as a series of potential threats, readers are encouraged to encounter them with a sense of wonder. In this way, curiosity, in the midst of a horrifying tale, grants Alice the tools to persistently navigate the uncertain world, Carroll the means to tell the story with aplomb, and the readers the chance to remember it fondly. Echoing these three roles of curiosity in telling the story of "Alice in Wonderland", we propose a cognitive and neurobiological model by which curiosity promotes maintenance of goal-pursuit through cognitive flexibility, aids emotion regulation through abstract information-processing, and may positively bias memory encoding through that process.

We posit a framework by which curiosity regulates emotion through co-occurring regulatory and encoding mechanisms. We construe emotion regulation through the lens of memory because affective memory is particularly important to future emotional well-being (Bowen et al., 2018). Affective memory has been observed to operate like a reinforcing feedback loop, such that more positive memories predict future emotionally positive encoding (Philippe et al., 2012; Philippe & Bernard-Desrosiers, 2017; Tov, 2012). Behaviorally, memory processes underlie decision-making (Biderman et al., 2020; Murty et al., 2016) and future simulation (Schacter et al., 2007), both of which are essential for goal-pursuit and subsequent regulatory chocies (Carver & Scheier, n.d.). Furthermore, the hippocampus (HPC), while often considered in relation to episodic encoding, also has a central role in emotional processing, particularly in the domain of safety learning (Phelps, 2004). Because of this, emotional states and neurobiological memory mechanisms can mutually inform one another (Goldfarb & Phelps, 2017), such that understanding of emotional outcomes can be aided by considering underlying memory processes, and vice versa. Indeed, memory related mechanisms embedded within regulatory contexts may be particularly adaptive in promoting overall well-being (Samide & Ritchey, 2021). For these reasons, our model is structured based on how regulatory and memory processes interact to predict emotional outcomes over time.

We contend that curiosity affords increased cognitive flexibility and abstraction, which serve as regulatory mechanisms that together guide information-processing. We hypothesize that these processes are largely reliant on cortical mechanisms, and are associated with increased activity in the left inferior frontal gyrus (LIFG), the dorsal anterior cingulate cortex (dACC), and the lateral pre-frontal cortex (LPFC). We then argue that curiosity also regulates emotion associated with negative events through subcortical circuitry, specifically by promoting dopaminergic modulation of memory encoding in the hippocampus (HPC) via the ventral tegmental area (VTA), in turn biasing information-processing away from the amygdala (AMY) and the medial temporal lobe (MTL). Drawing upon existing theories of affective memory, we suggest that the above processes together predict biasing of information during encoding away from narrow representations of threat towards more integrative, contextualized encoding of the event. Integrating extant research in emotion regulation and affective memory, we propose that this dual-implication of in-the-moment regulatory mechanisms (LIFG, dACC, and LIFG) and biased encoding mechanisms (VTA projections to the HPC) combine to predict both positive emotion during curious states and improved well-being over time.

In this paper, we first overview preexisting research on curiosity and various emotional outcomes, and highlight the need for a model that can account for mixed evidence. Then we review curiosity's memory benefits set in the broader foundation of the extant research on affective memory encoding to propose that curiosity may positively bias information during encoding. Next, we situate curiosity in an emotion regulation framework, emphasizing the regulatory roles of abstraction and cognitive flexibility that curiosity affords to both regulate emotional response during negative experience, and address alternatives to our memory hypothesis. Finally, we conclude with implications for the developmental trajectory of emotion regulation.

Curiosity's emotional outcomes

Empirical research on curiosity has largely conceived of curiosity as a particularly rewarding combination of an appetitive drive (interest; Berlyne, 2014) and a motivating information-gap or prediction error (deprivation; Loewenstein, 1994) that intrinsically motivates individuals to seek out information about phenomena (Dan et al., 2020; Litman, 2008; Litman et al., 2019; Shen et al., 2022). While both deprivation and interest predict that curiosity will lead to approach-oriented behavior, they produce mixed predictions regarding the utility of curiosity in goal-pursuit and the associated emotional impact of curiosity. While interest may distract one from gathering more useful information, it likely implies positive emotions of enjoyment and pleasure (Litman, 2005). In contrast, while curiosity motivated by deprivation may provide useful information, it also implies uncertainty and the accompanying aversive emotions (van Lieshout et al., 2021). Taken together, predicting the emotional outcome of curiosity is quite difficult. In this section, we review observed evidence for curiosity's emotional benefits, as well as opposing evidence for its potential negative effects. We then propose a novel theoretical conceptualization of curiosity as a mindset before introducing our model.

Contemporary study of curiosity often emphasizes the importance of emotional contexts and outcomes, and has regularly observed associations between curiosity and positive emotion (Silvia, 2008). Research in personality and individual differences has found that higher trait-level curiosity is associated with higher levels of cognitive flexibility (Kashdan et al., 2018), openness to experience (Silvia & Christensen, 2020), and tolerance of uncertainty (Birenbaum et al., 2019); all of which are in turn associated with reductions in anxiety and depression (Chiappelli et al., 2021; Deveney & Deldin, 2006; Gentes & Ruscio, 2011). Additionally, diary studies have found that individuals who report higher day-to-day curiosity also report more positive emotion and well-being (Lydon-Staley et al., 2020). Research examining the potential mechanisms underlying this association have found that curiosity helps individuals process adversity by enabling persistent approach-behaviors (Kashdan & Steger, 2007) and effective coping strategies (Drake et al., 2022). In summary, curiosity, observed either as a trait or a state, appears to both improve general well-being and bolster resources to navigate negative experiences.

While there is substantial evidence for the attributes of curiosity that support well-being, there is a growing body of research that suggests curiosity may have negative effects on emotional states, particularly as it pertains to resolving uncertainty. There is evidence that curiosity may be primarily motivated by aversive feelings of uncertainty (Hsee & Ruan, 2016), and that being curious following uncertainty negatively correlates with subjective reports of well-being (van Lieshout et al., 2021). Additionally, curiosity may not only be motivated by aversive feelings, but may also direct information-processing resources *towards* aversive information (Oosterwijk et al., 2019), or information that is not relevant for goal-achievement (Cabrero et al., 2019). In both cases, curiosity presents a situation in which negative affect could motivate information-seeking that either increases the probability of future negative affect (Oosterwijk, 2017), or prioritizes the resolution of uncertainty above other needs (Lau et al., 2020). This evidence suggests that curiosity may reflect a negative emotional experience that engenders information-seeking behaviors that could promote negative emotion or distract from the positive emotional benefits of goal-pursuit (Carver & Scheier, n.d.-b).

Taken together, this indicates a demand for a model of curiosity and emotion that can account for curiosity as being simultaneously motivated by negative affect, while nevertheless resulting in eventual positive emotion and overall well-being. Drawing upon mindset theory (Dweck & Leggett, 1988), we propose that deprivation and interest can be understood as commonly observed motivators of a *curious mindset*. Mindset theory broadly proposes that implicit beliefs can produce meaning systems that guide cognition and behavior, resulting in unique motivational outcomes (Hong et al., 1999). Here, we operationalize curiosity as a mindset structured by the implicit belief that phenomena can be reduced to information, and by extension phenomenology can be reduced to informational accrual. This conceptualization accounts for observed deprivation and interest motivations underlying information-seeking, while also expanding the scope of how one can arrive at a curious state. Additionally, it provides a theoretical justification for the subjective experience of conscious, agential instantiation of curiosity. We further propose that this mindset affords regulatory mechanisms during affective encoding that may account for these different observations if an initially negative experience comes to be recalled less negatively following the regulation afforded by a curious mindset. In other words, a curious mindset may promote effective coping over time through the regulatory and encoding mechanisms implicated by the reduction of an aversive experience to an information-gathering opportunity. Below, we propose a novel theoretical model linking curiosity as a mindset, affective memory mechanisms, and emotion regulation.

Curiosity and the Regulation of Affective Memory (CRAM)

We propose that, through a combination of regulatory and encoding mechanisms, curiosity regulates emotion *during* negative experience, *and* positively biases memory of the experience, to predict future well-being. We first identify dopaminergic memory benefits associated with curiosity (Gruber & Ranganath, 2019) that may positively bias memory during encoding, based on contemporary models of affective memory (Clewett & Murty, 2019). We next identify abstraction (Gilead et al., 2020; Hadar et al., 2021; Yudkin et al., n.d.) and cognitive flexibility (Kashdan & Steger, 2007; Kashdan et al., 2018) as regulatory mechanisms underlying curiosity's emotional benefits, that serve to increase psychological distance (Moran & Eyal, 2022) and maintain goal-oriented action (Kashdan et al., 2020) respectively. Finally, we identify two alternative positions or arguments against our framework, before arguing that the neural processes underlying abstraction and flexibility address these alternatives and support our proposed framework.

Curiosity and affective memory

Curiosity has consistently been known to improve learning and memory (Berlyne, 1978; Kang et al., 2009). These memory benefits are likely due to motivational systems implicated by curiosity (Murayama, 2022). Curious states tag information with incentive salience, such that the information becomes motivating in and of itself (Szumowska & Kruglanski, 2020; Litman, 2005; Murayama et al., 2019). Once curiosity motivates information-seeking behavior, the ventral tegemental area (VTA) exhibits increased connectivity with the HPC (Gruber et al., 2016; Gruber et al., 2014). The coupling of VTA and HPC activity results in dopaminergic modulation of encoding, which in turn prioritizes that information in memory (Gruber & Ranganath, 2019). We argue that this well-studied process for curiosity's memory and learning benefits, predicts positive biasing of information during encoding by providing more flexible, integrative representations of past events. To demonstrate this, we begin with an overview of the neurobiological pathways that prioritize affective information during encoding.

We focus on three distinct, but not mutually exclusive, theories concerning the prioritization of affective information during encoding. Each theory hypothesizes distinct projections into the HPC that meaningfully predict both the quality and strength of the memory. The first proposes an emotional-binding account, in which the encoding of detail within context enabled by the HPC (Diana et al., 2007) is superseded by projections from the central amygdala (cAMY) to the medial temporal lobe (MTL) that instead bind detail with emotion; thereby increasing the overall strength of the memory trace (Ritchey et al., 2019; Yonelinas & Ritchey, 2015). This proposed pathway may be particularly prominent for negative episodic memories, while projections from the lateral pre-frontal cortex (LPFC) to the HPC appear to encode more positive memories (Ritchey et al., 2011). The second theory proposes that, specifically in regard to the prioritization of negative episodic encoding, that amygdala-MTL connectivity increases emphasis on sensory detail. This subsequently increases the perceived vividness of the memory during retrieval (Bowen et al., 2018), which may underlie a focus on negative/distressing information. Positive memory may be similarly prioritized through amygdala-MTL connectivity, through basolateral amygdala (BLA) connectivity with the nucleus acumbens (NAC) that then projects to the HPC (Beyeler et al., 2018). The third theory proposes that the recollected emotion may be best predicted by the neuromodulation of hippocampal encoding, and associated motivational states, rather than the valence of any given event. Specifically, that arousal and noradrenergic modulation would predict encoding of highly salient sensory detail while behavioral activation and dopaminergic modulation would predict more flexible encoding of a wider-array of episodic detail (Clewett & Murty, 2019). In our contention that curiosity positively biases memory during encoding, we are aligned closely with this third theory in regard to centralizing the role of neuromodulation of encoding, though our framework is rooted in valence-driven conceptualization of these processes.

We propose that the dopaminergic motivational signals implicated by curiosity will result in our predicted positive affect at recall. However, the dopaminergic modulation of encoding implicated by curiosity, in and of itself, is not sufficient evidence for our framework for two key reasons. Firstly, there are alternative pathways to affective encoding that have been theorized that our framework must address (Bowen et al., 2018; Ritchey et al., 2019). Additionally, our suggestion that curiosity positively biases memory at both encoding and retrieval is currently ill equipped to explain *why* curiosity might motivate these memory mechanisms. We propose that curiosity implicates cognitive flexibility and abstraction as regulatory mechanisms that further elaborate and structure our framework by addressing alternative pathways to affective encoding, and providing explicative evidence for the motivation of our proposed processes.

Situating curiosity in an emotion regulation framework

To elaborate on the regulatory mechanisms afforded by curiosity and their impact on affective memory, we situate curiosity in relation to control-process theories of emotion and emotion regulation. Control-process theory proposes that self-regulation is motivated and maintained by an individual’s assessment of distance from their goal-states, and the required behavior and effort to reduce that distance (Carver & Scheier, 1982). As an extension of this account, emotion regulation is viewed as a form of self-regulation that is motivated by reduction of the distance between a current emotional state and an emotional goal-state (Tamir et al., 2020). For the purposes of this review, we focus on consideration of how curiosity increases a tendency for cognitive flexibility and abstract thought. In so doing, we aim to demonstrate that the regulatory benefits of curiosity are due to its tendency to increase abstract and flexible information-processing, which may result in positive biases at memory encoding and retrieval.

Curiosity implicates cognitive flexibility as a regulatory mechanism

A great deal of research has identified that cognitive flexibility can play an important role in negative emotion regulation (Pruessner et al., 2020), particularly in the context of goal pursuit. By cognitive flexibility, we refer to the ability to switch regulatory strategies to achieve one’s goals. One of the more prominent theories in this space is regulatory focus theory, which presumes that self-regulation, and by consequence emotion regulation, is informed by whether one’s goals are oriented towards approaching positive outcomes (i.e., promotion) or avoiding negative outcomes (i.e., prevention) (Scholer & Higgins, 2014). The efficacy of either regulatory focus is dependent on context (Scholer & Higgins, 2014; though see Frederickson, 2013 for an argument that promotion is nearly always more beneficial than prevention). Given that different contexts demand different regulatory focus, it is no surprise that being flexible in regulatory contexts is important to achieve regulatory success (Bonanno & Burton, 2013). Engaging cognitive flexibility not only increases likelihood of success by allowing flexible selection of goal-state and strategy to match context (Dajani & Uddin, 2015), but also predicts maintenance of goal-pursuit despite possible setbacks (Kashdan et al., 2020). Repeated regulatory failure is highly associated with a wide range of emotional and psychological difficulties (Romer et al., 2021); therefore, the impact of flexibility on self-regulation may explain its consistent association with emotional well-being (Kashdan & Rottenberg, 2010). Unfortunately, maintaining flexibility in the context of emotion regulation can require immense cognitive effort (Pruessner et al., 2020). We posit that evoking a curious mindset may provide an information-processing approach that promotes regulatory flexibility while requiring less effortful maintenance of goal pursuit with the absence of curiosity's motivational mechanisms.

Notably, curiosity is consistently associated with psychological flexibility, both at the level of personality traits (Birenbaum et al., 2019; Kashdan et al., 2018), and in associated brain activity (Hayden et al., 2011; Tang et al., 2012). At the personality level, both curiosity and cognitive flexibility are known to involve high openness to experience (Kashdan et al., 2020). Neurobiologically, both curiosity (Cervera et al., 2020) and flexibility (Dajani & Uddin, 2015) are associated with activity in the dorsal anterior cingulate cortex (dACC). The dACC is thought to monitor the value proposition of any given cognitively effortful response (Shenhav et al., 2013). This process in the case of cognitive flexibility is operationalized as monitoring the value of flexibly switching between goal-states (Worringer et al., 2019). In the case of curiosity, it may represent monitoring the value of resolving a prediction error through information-search (Gruber et al., 2014).

Curiosity is clearly distinct from flexibility in the implication of brain networks associated with motivation, like the ventral striatum (Kang et al., 2009). In fact, activity in the striatum is associated with the same prediction errors that appear to activate curiosity-related dACC activity (Hayden et al., 2011). This suggests that a fundamental aspect of cognitive flexibility, which is the evaluation of the cognitive effort required as worthwhile by the dACC, may be evoked by curiosity through motivational reward signals. Curiosity may motivate the effort necessary to maintain flexibility through dopaminergic signaling, thereby increasing the likelihood of regulatory success due to flexible selection of regulatory focus and goal-state. This may then result in encoding processes associated with behavioral activation rather than arousal, allowing for the possibility of more positive emotion at recall even if the experience at encoding was negative (Clewett & Murty, 2019). To directly tie this to a real-world example, consider an individual going through a difficult breakup. Adhering too strongly to one regulatory strategy (e.g., avoiding socializing with mutual friends) may be effective in the short-term, but may lead to problematic long-term outcomes. In contrast, we propose that taking a curiosity-focused mindset (i.e., I wonder how this situation will make me feel?) may lead to a more flexible regulatory approach that would involve both elements of prevention (e.g., avoiding checking social media on their birthday) and promotion (e.g., approaching said mutual friends to make new memories) would likely result in more positive post-breakup outcomes. That is, the curious individual may find that the reward proposition naturally implicated by flexible consideration of other goal-states may motivate cognitive, or regulatory, flexibility; thereby reducing the effort required to maintain flexibility. The curious individual can refocus attention and effort towards emotionally beneficent goals or strategies, rather than fixating on the failure proposition of the breakup.

Cognitive flexibility and the regulation of the basolateral amygdala (BLA) in memory encoding

To connect cognitive flexibility to our proposed curiosity and affective memory framework, we posit that curiosity implicates cognitive flexibility as a regulatory mechanism that would predict blunting of BLA response. While BLA projections to the ventral striatum have been observed to have positive memory effects (O’Neill et al., 2018), there is enough observed variation in the affective outcomes of amygdala-VTA connectivity (Walsh & Han, 2014) that the potential influence of the BLA on affective encoding during curiosity must be addressed. Furthermore, there is evidence for the importance of BLA-VTA coupling in the learning of conditioned fear in animal models (de Oliveira et al., 2011; de Souza Caetano et al., 2013), which has been substantiated in human models through evidence of BLA-VTA connectivity underlying memory mechanisms of post-traumatic stress disorder (Patel et al., 2016). Curiosity is associated with dopaminergic signals in the VTA (Murayama et al., 2019), but has not been associated with BLA activation. This is somewhat surprising given that BLA activity is associated with decision-making under uncertainty (Stolyarova et al., 2019), which likely represents a similar process to making information-seeking choices in response to a prediction error (Gruber & Ranganath, 2019). We contend that BLA activity has not been associated with information-seeking likely due to regulation of the BLA response to uncertainty by cognitive flexibility enabled by dACC activation during curiosity. The anterior cingulate cortex (ACC) has been observed to blunt fear conditioning through neural projections to the BLA (Jhang et al., 2018; Ortiz et al., 2019). It has been theorized that this regulation of the BLA reflects processes of cognitive flexibility assigning value to motivated behavior in response to uncertainty (Keefer et al., 2021; Soltani & Izquierdo, 2019). Taken together, this suggests that curiosity enables a flexible approach to conditions of uncertainty associated with dACC activation, which then predicts blunting of the BLA response to uncertainty, resulting in motivated behavior and "clean" VTA projections to the HPC during encoding. Therefore, the cognitive flexibility that promotes maintenance of goal-pursuit behaviorally (Kashdan et al., 2020) appears to neurologically predict dopaminergic modulation of encoding without BLA input, making it more likely to result in positive affect at recall (Clewett & Murty, 2019).

Curiosity implicates abstraction as a regulatory mechanism

There is reason to suspect that cognitive flexibility is not the only regulatory mechanism that curiosity facilitates, and that impacts memory encoding. States of curiosity are highly related to psychological distance, as evidenced by the increase in perceived information needs, and subsequent information-seeking choices, observed when individuals adopt a psychologically distanced standpoint (Halamish & Liberman, 2017). Psychological distance is closely connected to the concept of abstraction. Indeed, abstraction of a phenomena is thought to be predicated on psychological distance (Gilead et al., 2020) and explicit processing of psychological distance is thought to require abstraction (Liberman & Trope, 2014). Additionally, both psychological distance and abstraction predict increased information-seeking, and integration of information into informed, holistic concepts (Hadar et al., 2021). Neurologically, both abstraction (Gilead et al., 2020) and curiosity (Kang et al., 2009) are associated with activity in the left inferior frontal gyrus (LIFG). The LIFG has been observed to represent abstract concepts (Wang, 2010), process semantic conflict (Roelke & Hofmann, 2020), and control semantic retrieval (Davey et al., 2016). Its invocation during curiosity is likely related to controlling relevant semantic recall and conceptual information-search to inform or resolve abstracted predictions (Gilead et al., 2014; Shen et al., 2022). Activity in the LIFG would therefore be particularly relevant to abstraction implicated by curiosity, as its activation would underlie both the resolution of semantic conflict (e.g. prediction error) *and* the cognitive control of higher-order information seeking.

The psychological distance that curiosity implicates, and that is required for abstract information-processing, has been observed to be emotionally beneficial, allowing individuals to process negative experiences without overwhelming negative emotion (Ayduk & Kross, 2010). Indeed, even the low-effort self-distancing act of referring to oneself in the third person has demonstrated regulatory benefits (Moser et al., 2017). Kross and Ayduk (2011) have proposed that these benefits may be a result of abstract meaning-making processes that psychological distance enables. Furthermore, it has been theorized that whether or not an abstract, distanced perspective is employed when questioning the causal structure of negative experiences may be what differentiates rumination from reflection (Kross et al., 2005). This explanation is further evidenced by the observation that individuals suffering from depression do not relive negative emotions associated with past memories if they recall the memories from a psychologically distanced standpoint (Kross et al., 2012). Considering these findings in relationship to observations of the LIFG and concept-driven recall that curious and abstract information-processing employ, it appears that curiosity may regulate emotion by allowing individuals to approach negative experiences as sources of conceptual information rather than emotional stimulation. In relation to our example of the breakup, a curious individual may recall the relationship in order to inform higher-order conceptual question such as “What form of romantic attachment do I prefer?” In contrast, an individual who processes the breakup in relation to concrete meanings is more likely to relive episodic memories that stimulate negative emotion, and may be at increased risk of rumination. Curiosity, by implicating abstraction, enables individuals to process phenomena from a distance, thereby regulating emotion by prioritizing conceptual reflection over episodic simulation. While the emotional benefits of psychological distance reviewed above, in and of themselves, do likely result from curiosity, we still argue that abstraction is the more relevant regulatory mechanism implicated by curiosity. We contend this for two primary reasons: 1) The same emotional benefits observed during psychologically distanced conditions are likely to occur during abstraction given that abstraction necessitates psychological distance (Gilead et al., 2020), and 2) The impact of the dual-implication of curiosity and abstract information-processing on encoding mechanisms reveal an additional emotionally beneficial role of abstraction that is distinct from psychological distance alone.

Abstraction and the possible semanticization of episodic detail at encoding

We draw upon extant research into semanticization of episodic detail (Renoult et al., 2019) and multiple-trace theory (Moscovitch & Gilboa, 2021) to suggest that the abstract information-processing employed by curiosity at encoding could reduce episodic simulation at recall. Semantic memory is thought to form from episodic memory over time (Klooster et al., 2020). There is an observed process by which original episodic memory traces in the HPC are gradually recapitulated into cortical traces associated with personal semantic representations (Renoult et al., 2012). As episodic memory traces coexist with eventual interconnected semantic memory traces, there appears to be competition between recalling episodic detail and semantic concepts that may be resolved by cognitive control mediated by the LIFG (Vatansever et al., 2021). This suggests that while the LIFG has been associated with resolution of inter-semantic conflict (Becker et al., 2020), it may also serve to determine whether or not the effort required to recall and process higher-order semantic meanings is applied (Stampacchia et al., 2018). We propose that abstraction and the associated LIFG activity during encoding may result in bias towards encoding semantic meaning rather than episodic detail. There is evidence for stronger encoding of semantics through LIFG-HPC connectivity (Kaneda et al., 2017), especially if the semantics being encoded relate to prior knowledge (Bein et al., 2020). Abstraction, and curiosity, are associated with globalizing semantic processes (Halamish & Liberman, 2017; Yudkin et al., 2019), increasing the likelihood that information at encoding would be perceived relative to prior knowledge during encoding. Taken together, we propose that abstraction's cognitive emphasis on global meaning-making processes recruits the LIFG during information seeking, resulting in semanticization of episodic detail at encoding rather than over time with repeated recall. This semantic emphasis at encoding could then result in less episodic simulation of negative life events encoded while curious. We contend that this early semanticization of episodic detail would be emotionally beneficial, given the central importance of self-semantics to well-being across the lifespan (Philippe & Bernard-Desrosiers, 2017; Rathbone et al., 2015).

Curiosity and recruitment of the lateral pre-frontal cortex

One possible argument against our model is that it requires activation from the LPFC to achieve the motivated behavior that would result in dopaminergic VTA inputs to the HPC. While reward-related positive emotion memory benefits are consistently observed during information-seeking (Gottlieb et al., 2013) and the relief of curiosity (Murphy et al., 2021), they are less consistent during initialization of the curious feeling itself. Additionally, coupling of the VTA with the LPFC is an important aspect of the positive pathway to emotion encoding (Ritchey et al., 2011), and activity in the LPFC has been demonstrated to predict VTA-related motivation (Ballard et al., 2011) that may serve to transform curious feeling into information-seeking behavior. We argue that the regulatory mechanisms of abstraction and flexibility, and their recruitment of the LIFG and dACC, predict LPFC recruitment and the motivated information-seeking behavior necessary to achieve VTA response.

Abstract and flexible information processing, and the accompanying activity in the LIFG and dACC respectively, is highly associated with activity in the LPFC. Abstraction appears to recruit LPFC activity, likely due to simultaneous association of LIFG and LPFC activity with cognitive control and inhibition (Nee & D’Esposito, 2017; Swick et al., 2008). Curiosity’s implication of dACC appears connected to the coding of the subjective value of acting on perceived uncertainty (Hayden et al., 2011; Kang et al., 2009; Shenhav et al., 2013; Westbrook et al., 2019). We have argued that reward predictions in the dACC may reduce the effort required to engage cognitive control in the LPFC necessary to achieve greater regulatory success (Etkin et al., 2015; Frank et al., 2014). Further substantiating this possibility is consistent evidence that the dACC may directly regulate cognitive control processes in the LPFC through subjective valuation of predicted rewards (Khamassi et al., 2015; Lake et al., 2019). In particular, individuals who are reactive to surprise, a well-studied instigator of curiosity and information-seeking (Gottlieb et al., 2020), are more likely to engage cognitive control through dACC and LPFC coupling (Vassena et al., 2020). This process of surprise signals predicting dACC and LPFC interconnectivity that underlies effortful cognitive engagement has been theorized as a fundamental mechanism driving cognitive flexibility generally (Qiao et al., 2022). Additionally, dACC decoupling from the LPFC has been identified as a neural marker of cognitive fatigue (Müller & Apps, 2019; Wylie et al., 2020), suggesting that valuation of potential informational reward through flexible information-processing in the dACC may be essential for maintaining cognitive control in the LPFC. Taken together, abstract and flexible information-processing implicated by curiosity would improve cognitive control of approach behaviors through connectivity with LPFC, increasing the likelihood of motivated information-seeking and the subsequent VTA inputs to the HPC during encoding.

CRAM framework

Thus far, our framework proposes that curiosity employs flexible and abstract information-processing as regulatory mechanisms, and the underlying neural circuitry of these mechanisms further predicts dopaminergic modulation of memory encoding and subsequent positive affect at recall. Given existing theories of affective memory encoding, we identify two primary reasons against this possibility. The first alternative is that the arousal associated with the uncertainty that commonly accompanies curiosity would maintain amygdala-MTL connectivity, therefore resulting in the emphasis on sensory detail and emotion binding that is associated with negative affect (Bowen et al., 2018; Lee et al., 2015). We argue that that the combination of regulation of amygdala subregions by the dACC through cognitive flexibility, and the semanticization of episodic detail through the recruitment of the LIFG by abstraction, together make this alternative unlikely. The second alternative is that LPFC activation, and the associated motivated behavioral control that appears necessary to achieve the dopaminergic modulation of encoding, may not be sufficiently implicated by curious feeling alone. We have argued that the regulatory mechanisms of flexibility and abstraction predict recruitment of the LPFC, and may be a key factor in motivating information-seeking from initial curious feeling.

Implications

In this paper, we have argued that curiosity regulates emotion in memory through interacting regulatory and encoding mechanisms. We contend that the mechanisms of abstraction, flexibility, and motivation combine to predict decreased activations of regions associated with negative emotional encoding, and increase the likelihood of dopaminergic encoding of positive emotion in memory. Through these mechanisms, negative experiences can be remembered more positively through application of curiosity, either in the moment or in later consideration of the event in memory. To make this more concrete, consider two individuals who recently experienced a breakup – a curious processor, and a concrete processor. The curious processor may focus on other goals (e.g., career) despite the experience of failure, while also processing the breakup based on abstract conceptual meaning-making. Both of these processes are likely to be emotionally beneficial in the moment, encouraging adaptive coping and reduction of negative episodic simulation. Additionally, given the recruitment of the LIFG and dACC to support these processes, the curious individual is likely to encode information surrounding the breakup through pathways of LPFC and VTA projections into the HPC. Later on, as they attempt to re-enter dating life, they may recall the breakup relative to meaning-making processes rather than ruminate on highly specific detail. This overall positivity bias in memory, and semanticization of the negative experience at encoding, is further likely to predict future regulatory success (Samide & Ritchey, 2021) and adaptive decision making (Murty et al., 2016). The concrete processor, on the other hand, may be distracted from other goals and focused on episodic detail, due to increased arousal-based projection of amygdala responses to the MTL. This would predict avoidant behavior in the moment, as well as vivid episodic encoding of sensory detail from the negative event itself. The concrete individual then will likely have to depend on much more effortful cognitive control in the later choice to begin dating again, due to the negative and highly detailed memory of the previous breakup (Williams et al., 2022). In this way, we contend that curiosity through regulatory and encoding mechanisms promotes well-being during negative experience, and through life. Given the importance of memory processes to emotion regulation (Engen & Anderson, 2018) and future decision-making (Murty et al., 2016), we believe curiosity's dual implication of regulatory and memory mechanisms makes it an uniquely effective approach to regulating behavior and emotion over time. Now we discuss the social and developmental implications of our model.

Developmental trajectories and adolescent emotion regulation

Prominent theories of adolescent regulation propose that the neural systems underlying regulation, primarily within the prefrontal cortex, are underdeveloped leading to poor self-regulation during adolescence (Steinberg et al., 2018). This possibility is further evidenced by the effects of specific regulatory training on prefrontal structure and response in adolescence

(Delalande et al., 2020). However, we contend that, rather than taking an approach to adolescent regulation that emphasizes deficits and vulnerabilities (Modecki et al., n.d.), we ought to focus our attention on regulatory mechanisms that are particularly reactive and well developed for that age group (Davidow et al., 2016; Telzer, 2016). We contend that our proposed framework of curiosity's promotion of well-being during negative experience, and over time in memory, emphasizes behavioral and neural responses that could be considered a skillset of most adolescents. Adolescents appear sensitive to motivational systems, like the VTA response implicated by curiosity (van Duijvenvoorde et al., 2016), and may be particularly sensitive to social rewards (Ethridge et al., 2017). Furthermore, this social sensitivity appears to make adolescents even more likely to engage in information-seeking behavior than adult populations, due to peer influence (Silva et al., 2016). Therefore, it is possible that adolescents may engage in curiosity more often, and be more impacted by the underlying positive encoding mechanisms that we have outlined. And indeed, it appears that dACC associated flexibility (Hauser et al., 2015) and LIFG associated abstraction (Barch et al., 2018) are both key aspects of adaptive adolescent decision making. From this perspective, the reduced inhibition and increased risk taking in adolescence (Chein et al., 2011; Smith et al., 2018) may be adaptive, if it encourages greater recruitment of dopaminergic motivated behavior that may predict more positive and meaning-rich memories to inform later life regulation and decision-making. Research into the long-term regulatory benefits of heightened curiosity in adolescence should be done to examine whether our framework may demonstrate an adaptive nature underlying adolescent risk-taking.

Conclusion

We have proposed that curiosity promotes well-being through a combination of regulatory and encoding mechanisms. Within the construction of our framework are a diverse array of interrelated hypotheses that must be tested to confirm or reject aspects of this framework. Among the most important of these, in our mind, is the possibility of semanticization of episodic detail at the encoding of an initial trace. Often, through the passage of time, deeply emotionally difficult memories begin to lose their sting as we can place them in relation to a broader, abstracted narrative sense of self. Is it possible that curiosity could produce this kind of distanced, narrative structure of self, earlier in life? This possibility may be quite important for the development of holistic psychological well-being, and the role of various therapeutic techniques in addressing past negative experience. We hope that this possibility, as well as the other possibilities afforded by this framework, stirs the curiosity of the reader.

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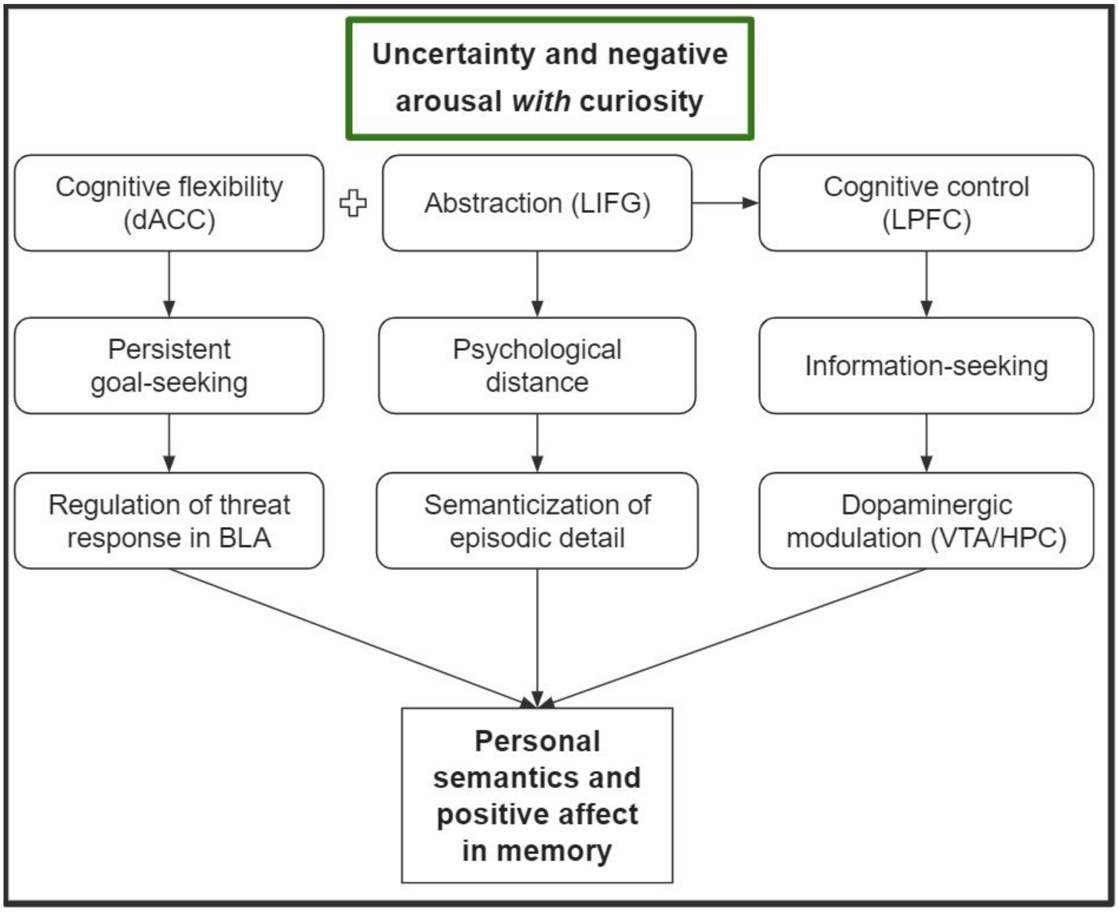
Figures

Figure 1: Curiosity and the regulation of affective memory (CRAM) framework: dorsal anterior cingulate cortex (dACC), left inferior frontal gyrus (LIFG), lateral pre-frontal cortex (LPFC), basolateral amygdala (BLA), ventral tegemental area (VTA), and the hippocampus (HPC)



Uncertainty and negative arousal *with* curiosity

Cognitive flexibility (dACC)

Abstraction (LIFG)

Cognitive control (LPFC)

Persistent goal-seeking

Psychological distance

Information-seeking

Regulation of threat response in BLA

Semanticization of episodic detail

Dopaminergic modulation (VTA/HPC)

Personal semantics and positive affect in memory