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Curiosity in old age: A possible key to achieving adaptive aging

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ABSTRACT

Curiosity is a fundamental part of human motivation that supports a variety of human intellectual behaviors ranging from early learning in children to scientific discovery. However, there has been little attention paid to the role of curiosity in aging populations. By bringing together broad but sparse neuroscientific and psychological literature on curiosity and related concepts (e.g., novelty seeking in older adults), we propose that curiosity, although it declines with age, plays an important role in maintaining cognitive function, mental health, and physical health in older adults. We identify the dopaminergic reward system and the noradrenergic system as the key brain systems implicated in curiosity processing and discuss how these brain systems contribute to the relationship between curiosity and adaptive aging.

> Life was meant to be lived, and curiosity must be kept alive. One must never, for whatever reason, turn his back on life.
>
> - Eleanor Roosevelt (1961)

Curiosity is a fundamental motivation in humans. Although the literature still lacks a widely accepted definition of curiosity and there have been several variations in its definition (Berlyne, 1954; Collins et al., 2004; Kidd and Hayden, 2015; Litman, 2008; Loewenstein, 1994; Oudeyer et al., 2016; Silvia, 2005, 2008), most researchers agree that curiosity represents a motivation or desire to seek and learn new information by exploring novel or uncertain environments (Kashdan and Silvia, 2009). Especially visible in early childhood, curiosity has received attention in the literature of child development (Engel, 2011; Smock and Holt, 1962) and education (Grossnickle, 2016; Klahr et al., 2011; Oudeyer et al., 2016). These studies have found that curiosity plays a central role in children's learning, predicting academic achievement and achievement motivation (Renninger and Hidi, 2016; Von Stumm et al., 2011). Curiosity also plays critical roles beyond the context of child development and education, supporting a variety of activities like consumer behaviors (Steenkamp and Baumgartner, 1992), job performance (Mussel, 2013), and scientific discoveries (Simon, 2001).

In the current paper, we provide a literature overview of one of the most underappreciated topics on curiosity—curiosity in old age. We argue that, although curiosity generally declines with age, it plays an important role in maintaining cognitive function, mental health, and physical health in older adults. In contrast to the literature in child development and education, the existing literature on curiosity in older adults is rather sparse and the few relevant topics are largely isolated from each other. Furthermore, whereas some studies examine curiosity by focusing on a phasic emotional and motivational state evoked when faced with novel and interesting stimuli, other studies measure individual differences in trait curiosity (individual differences in a tendency to experience curiousity; Litman and Spielberger, 2003) using self-reported questions, with little attempt to compare or reconcile findings across the different methodologies. In addition, studies on similar concepts (e.g., novelty seeking, experience seeking and sensation seeking) provide useful insights into curiosity, but this link tends to be overlooked in the existing literature. Our aim in the current paper is to join these different lines of research and assert the importance of curiosity in the aging population.

1. Effects of age on curiosity

Previous studies on subjective feelings of curiosity and aging suggest that normal aging leads to a decline in at least some aspects of curiosity. For example, in a cross-sectional survey study on a nationally representative sample in the UK, Robinson et al. (2017) showed a decline from early to late adulthood in three distinct dimensions of curiosity: interpersonal curiosity, a desire to find out information about other people, such as feelings of other people and what other people do; epistemic curiosity, an intellectual desire for new knowledge; and intrapersonal curiosity, a desire to find out new information about the self (see also Renner, 2006).

This age-related decline in curiosity is consistent with findings from studies of personality traits that are related to individual differences in

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trait curiosity. One example is openness to experience from the Big Five personality traits (Kashdan et al., 2004, 2009), which refers to individuals' willingness to explore, tolerate, and consider new and unfamiliar ideas and experiences (McCrae and Costa, 1987). Previous research has shown that, although scores for some personality traits increase with age (e.g., agreeableness; conscientiousness), openness to experience decreases with age (Costa et al., 2000; McCrae et al., 1999, 2000; Ziegler et al., 2015). Another trait which is related to curiosity is sensation seeking. Sensation seeking represents individual differences in the 'optimal level of stimulation' and refers to one's tendency to seek varied, novel, complex, and intense sensations and experiences (Zuckerman et al., 1980). Like openness to experience, sensation seeking appears to decrease with age (Lawton et al., 1992; Zuckerman et al., 1978). Closely related to sensation seeking, age-related declines in subjective feelings of stimulation seeking (i.e., a tendency to take part in stimulating activities) have also been confirmed via longitudinal study (Giambra et al., 1992). Research on apathy—a *lack* of motivation and interest, including indifference towards having new experiences—further reveals that normal aging is associated with increased apathy (Brodaty et al., 2010), consistent with age-related declines in curiosity.

Age-related reductions in exploratory behaviors in novel situations are also evident in animal research (e.g., Mroczek and Kolarz, 1998; Van Waas and Soffié, 1996). In one study, for example, young and old rats were habituated to two bottles with water for five days; on the sixth day, water in one of the bottles was replaced by a saccharin solution (Collier et al., 2004). Young rats preferred the saccharin solution over the water in the other bottle due to its novelty. In contrast, old rats showed reduced preference for the novel saccharin solution over the water bottle (see also Dellu et al., 1994). In summary, previous research suggests that normal aging is associated with reduced curiosity and reduced exploration behaviors in novel environments.

2. Brain mechanisms underlying curiosity in old age

What are the brain mechanisms underlying these age-related changes? To address this question, in this section, we will first provide a brief review of the brain mechanisms underlying curiosity and then explain how normal aging affects these brain regions.

2.1. Brain mechanisms of curiosity

While research on the neural mechanisms underlying subjective feelings of curiosity is still sparse, substantial research has addressed the neural mechanisms underlying exploration driven by novelty and uncertainty (for a review see Schomaker and Meeter, 2015). Novelty is defined as per the number of times that the stimulus has been previously encountered, while uncertainty is defined as per the unreliability of consequent outcomes (Gottlieb et al., 2013; Yu and Dayan, 2005). Thus, these two concepts are related but can be independently operationalized (e.g., one can feel uncertain about an outcome irrespective of whether the outcome is familiar or novel). Nevertheless, previous studies show some overlap in the brain regions involved in these processes and indicate the possibility that brain regions implicated in rewards and emotion play important roles in curiosity.

The first set of regions implicated in curiosity is the mesolimbic dopaminergic system (Fig. 1A). Exposure to novel stimuli induces activation of subcortical reward-related regions, including the nucleus accumbens (NAc), substantia nigra (SN), and ventral tegmental area (VTA; Axmacher et al., 2010; Bunzeck and Düzel, 2006; Bunzeck et al., 2014; Krebs et al., 2011; Wittmann et al., 2007, 2008). Individuals with high novelty-seeking tendencies also show greater activity in these regions than those with low novelty-seeking tendencies when exposed to novel stimuli (Krebs et al., 2009). Animal research provides further support for the role of the dopaminergic system in curiosity (Bardo et al., 1996): when animals are exposed to a novel environment, they show increased dopaminergic signals in the NAc (Legault and Wise, 2001; Piazza et al., 1991; Rebec et al., 1996, 1997) and increased firing rates of dopaminergic neurons in the SN (Ljungberg et al., 1992).

Recent neuroimaging studies have examined the neural mechanisms underlying curiosity more directly by employing tasks that induce subjective feelings of curiosity. These studies also indicate the importance of the dopaminergic system in curiosity (Kang et al., 2009; for a review see Kidd and Hayden, 2015). For example, Gruber and colleagues presented participants with trivia questions that differed in curiosity levels and found that trivia questions with higher curiosity was associated with stronger activity in the striatum and SN/VTA (Gruber et al., 2014). The striatum has been also implicated in the relief of perceptual curiosity (i.e., when curiosity triggered by the presentation of ambiguous visual input was satisfied by disambiguation; Jepma et al., 2012).

The studies described so far have focused on the dopaminergic reward-related areas, but accumulating evidence suggests that processing of novel and uncertain stimuli is also associated with the noradrenergic system (Fig. 1B), in particular the locus coeruleus (LC), a primary source of norepinephrine in the brain (e.g., Devauges and Sara, 1990; Gompf et al., 2010). Indeed, pupil dilation, a peripheral measure of LC activity (Joshi et al., 2016; Murphy et al., 2014), tracks unpredictability during tasks (Lavin et al., 2014). A recent neuroimaging study suggests that the LC is involved in processing uncertainty in humans (Payzan-LeNestour et al., 2013). In addition, changes in pupil dilation owing to uncertainty have been associated with better learning rates (Nassar et al., 2012). Likewise, phasic arousal induced by something emotional (which is associated with the LC activity) modulates learning and hippocampal functioning (Mather et al., 2016; Sakaki et al., 2014). Thus, the LC may also be related to curiosity-enhanced learning.

Animal studies further support the role of the LC in processing novelty and uncertainty (Delini-Stula et al., 1984; Harro et al., 1995). In one study, rats were habituated to a box which included nine holes symmetrically cut in the floor (Devauges and Sara, 1990). After habituation, objects were added in four holes and the rats were given idazoxan (an alpha2 adrenergic antagonist) or a control treatment. Idazoxan increased the time that rats spent exploring the holes with novel and unexpected objects, particularly those with complex objects, but did not affect exploration of the empty holes. Subsequent research confirms that administration of alpha2 adrenergic receptor agonists and beta receptor antagonists eliminate this preference towards holes with novel objects (Sara et al., 1995; see also Vankov et al., 1995).

2.2. Effects of age on brain regions important for curiosity

As reviewed in the previous section, the dopaminergic system and the noradrenergic system underlie exploration behaviors based on novelty and uncertainty in young adults and animals. Previous research also suggests that similar brain regions play critical roles in curiosity in older adults. For example, exposure to novel stimuli evoked activation in the SN/VTA in older adults like that seen in younger adults (Bunzeck and Düzel, 2006; Bunzeck et al., 2007). Norepinephrine release in the cingulate cortex—a region which has strong projections from the LC (Jones and Moore, 1977)—was also associated with intact exploratory behaviors in novel environments in old rats (Collier et al., 2004).

The dopaminergic system and the noradrenergic system are also susceptible to age-related decline. Past research has documented age-related declines in the striatum structure (Raz et al., 2003; Walhovd et al., 2005), striatal dopamine levels (Collier et al., 2007; Haycock et al., 2003), the number of dopaminergic D1 and D2 receptors in the striatum (Rinne et al., 1993; Rinne et al., 1990), responsivity of the striatum to reward learning (Chowdhury et al., 2013; Eppinger et al., 2013; Schott et al., 2007), and D2 receptor binding in the striatum (Bäckman et al., 2000; for reviews see Bäckman et al., 2010;Düzel et al., 2010; Kaasinen and Rinne, 2002; Reeves et al., 2002). Previous research has also shown increased iron accumulation in the striatum with