Knowledge for the sake of knowledge:

Understanding the relationship between curiosity, exploration, and reward

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Abstract

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Curiosity has long been a topic of scientific interest, but it encompasses so many potential traits and behaviors that it has been difficult to precisely target the cognitive and neural mechanisms that drive it. Recent work has reinvigorated the scientific approach to this topic by shifting from trait-level questions to a neurobiological perspective that emphasizes behavior, exploration and information-seeking. By viewing information as a reward, this research has leveraged the extensive body of work on reward processing to understand curiosity as a type of intrinsically motivated, goal-directed behavior. However, this information-as-reward framework raises a host of new questions about how curiosity develops and how it drives learning. In this dissertation, I aimed to test this framework and to address a series of questions about how curiosity drives exploration, learning, and memory.

Chapter 1 addresses the question of how curiosity changes across the adult lifespan and tests whether these changes mirror well-established declines in dopamine transmission and reward sensitivity. The first study in this chapter found that, rather than showing declines in curiosity, older adults in fact displayed behaviors that reflected increases in curiosity. They were more willing to wait for information than younger adults and were equally able to remember the information they learned. The second study sought to replicate these results and to examine their neural substrates using fMRI. This study found that older and younger adults displayed equal levels of curiosity and memory. Results from fMRI also showed similar effects for both age groups: increased activation in brain regions associated with reward processing, as well as semantic memory, was related to curiosity and to memory.

Chapter 2 explored the other end of development and examined changes in curiosity from late childhood into early adulthood. In this study, we focused on two different conceptualizations of curiosity -- willingness to wait (as in Chapter 1) and also a new measure of exploratory visual behavior. Results showed increases in both waiting and visual exploration between childhood and adulthood. These changes in curiosity were also accompanied by improvements in memory. These findings, like those in Chapter 1, provide evidence against the hypothesis that curiosity declines with age, and also expands our understanding of how different measures of curiosity-driven behavior may relate to one another.

Chapter 3 addresses a fundamental question about how to evaluate curiosity and how different forms of curiosity cluster together. Using a large online sample, we obtained two separate groups of measures: measures of curiosity-driven behaviors (willingness to wait, ratings of interest about specific questions, curiosity-related memory), and measures of curiosity as a trait. Additionally, we obtained measures of traits and behaviors though to be related to curiosity, including impulsivity, need for cognition and willingness to wait for monetary rewards. Results revealed that different aspects of curiosity-related behavior cluster together, and that while there was a relationship between self-report and behavioral measures, there were also more nuanced differences in the relationships between different behaviors.

Overall, the results from these three lines of research advance our understanding of curiosity by examining the extent to which curiosity is similar to reward processing, testing how it changes across the lifespan, and comparing different types of curiosity. The findings also open up new questions about the influence of other cognitive processes on curiosity and suggest ways in which we can better study how curiosity drives exploration and learning.

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For Evie, who is always curious

General Introduction

Many diverse behaviors are attributed to curiosity. Trying a new restaurant, googling for an answer, taking a class or pressing a button to see what happens can all be examples of curiosity-driven behavior. However, it has been difficult to pinpoint the specific cognitive and neural mechanisms that underlie curiosity. While some researchers have tried for broad, encompassing definitions (e.g. a drive state for information; Kidd & Hayden, 2015), a number of other aspects have been proposed as central to understanding curiosity, including the desire to know, exploratory behavior, the roles of novelty, uncertainty and complexity, and influence of arousal and emotion (Grossnickle, 2016). Recently, the field of curiosity research has experienced renewed energy as studies have begun taking a neurobiological approach to examining underlying mechanisms (Kidd & Hayden, 2015). One main insight from these studies is that information can serve as a reward, relying on the same brain networks as other reward processes (Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Gruber, Gelman, & Ranganath, 2014; Kang et al., 2009; Marvin & Shohamy, 2016). This framework has brought about new discoveries, but also new questions about the nature of curiosity, how it drives exploration and supports memory, and how it relates to other psychological processes.

Curiosity and Reward

One of the key features of curiosity is that it is intrinsically motivated (Kidd & Hayden, 2015; Pierre-Yves Oudeyer & Kaplan, 2007): we pursue information when we do not have to, or when there is no obvious benefit to doing so, or even when there is a cost associated with it. As noted by Loewenstein (1994), the sense of satisfaction when curiosity is sated can be pleasurable. A number of recent studies have drawn parallels between curiosity and reward-seeking, and found that people assign value to information, even when it does not have strategic utility. People are willing to exchange money, wait for lengths of time, and even risk electric shocks to gain information like the answers to trivia questions, the outcomes of lotteries, and solutions to magic tricks (Charpentier, Bromberg-Martin, & Sharot, 2018; Kang et al., 2009; Kobayashi & Hsu, 2019a; Lau, Ozono, Kuratomi, Komiya, & Murayama, 2018; Marvin & Shohamy, 2016; van Lieshout, Vandenbroucke, Müller, Cools, & de Lange, 2018). Just as the anticipation of monetary rewards has been shown to enhance memory (Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, 2006), curiosity can improve memory both for the information that is learned and for incidentally encountered information seen when in a high-curiosity state (Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016).

The behavioral findings that link curiosity to reward-seeking have led researchers to propose that curiosity may be based on the same neural mechanisms that process extrinsic rewards, including dopaminergic mesolimbic circuits, areas of the prefrontal cortex, orbitofrontal cortex, and the striatum (Arias-Carrión, Stamelou, Murillo-Rodríguez, Menéndez-González, & Pöppel, 2010; Bartra, McGuire, & Kable, 2013; Hare, O'Doherty, Camerer, Schultz, & Rangel, 2008; McClure, York, & Montague, 2004; O'Doherty, 2004). Multiple task paradigms, using a range of information modalities, have demonstrated increases in activation in these regions related to high curiosity (Charpentier et al., 2018; Gruber et al., 2014; Kang et al., 2009; Lau et al., 2018). This has led to assertions that the subjective value of information is processed by the brain in the same way as objective reward value (Kobayashi & Hsu, 2019a).

Curiosity has a strong positive influence on memory, and research on curiosity in the brain has shed light on the mechanisms driving this effect. Kang et al. (2009) found activation in regions related to episodic memory when participants saw an answer they did not know, and the level of activation was modulated by self-reported levels of curiosity. They proposed that this increased activation may relate to improvements in memory for high-curiosity information. Gruber et al. (2014) tested this by examining whether curiosity related activation predicted subsequent memory. Their results showed that question-evoked activation in the nucleus accumbens and the hippocampus predicted memory for high curiosity answers but not low curiosity ones. Furthermore, they found that increased activation during answer anticipation also predicted memory for unrelated information that was presented during this time, suggesting that states of curiosity can benefit learning for a much broader array of information beyond specific targets.

The information-as-reward framework is useful structure for studying curiosity, and it has provided compelling evidence for the parallels between intrinsically and extrinsically motivated behavior. However, questions still remain about the scope of this relationship, and about how and when other cognitive processes are involved. The reward framework makes specific and testable predictions about how curiosity should be affected by a variety of conditions, given the extensive work that has been conducted in studies of extrinsic rewards. One such prediction deals with how curiosity may change across the lifespan.

Curiosity across the lifespan

Conventional wisdom on curiosity closely associates it with childhood and youth. If curiosity is a process similar to reward sensitivity, then changes in curiosity across the lifespan should track with age-related changes in reward processing. Healthy aging is characterized by distinct behavioral changes in reward processing, which have been linked to changes in the structure and function of dopaminergic reward circuits (Dreher, Meyer-Lindenberg, Kohn, & Berman, 2008; Eppinger, Hämmerer, & Li, 2011). Older adults show deficits in reward association learning and decreased sensitivity to immediate monetary rewards (Eppinger et al., 2011; Tripp & Alsop, 1999; Eppinger, Nystrom, & Cohen, 2012; Green, Fry, & Myerson, 1994). Based on this, curiosity would be expected to decrease with age as sensitivity to rewards also decreases (Sakaki, Yagi, & Murayama, 2018).

However, experimental evidence for age-related changes in curiosity is sparse and contradictory. While one study found that trait-level curiosity decreases with age across early, middle and late adulthood (Robinson, Demetre, & Litman, 2017a), another study of adults between 17 and 92 that examined trait level curiosity, both cross-sectionally and longitudinally, found no systematic changes in curiosity with age (Giambra, Camp, & Grodsky, 1992).

Findings of curiosity-induced changes in behavior during aging are also inconsistent. A study on perceptual curiosity using free-viewing of images found no differences in patterns of exploratory eye movements between middle-aged and older adults (Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1994). Two recent studies using trivia questions found that older adults' self-reported curiosity ratings were equal to (Galli et al., 2018) or higher than (McGillivray, Murayama, & Castel, 2015) the curiosity ratings of younger adults, and both studies showed curiosity-driven memory benefits for both age groups. While there is evidence that reward processing related to the dopaminergic system is impaired in older adults, there is not enough published evidence to conclude that the same is true for curiosity.

Studying curiosity at the other end of the lifespan presents another opportunity to investigate its relationship with reward, as well as to address intrinsically interesting questions about curiosity during development. Curiosity is essential to the type of early learning that children must do in order to make sense of the world (Kidd & Hayden, 2015). Research on children as young as infants shows strong preferences for exploring novel, ambiguous and uncertain stimuli (Kidd & Hayden, 2015; Wentworth & Witryol, 2003).

In the reward domain, adolescence has been shown to be a period of high reward sensitivity. Studies have shown that reward sensitivity, risk-taking, and related neural activation in the striatum peak during adolescence (Braams, van Duijvenvoorde, Peper, & Crone, 2015; Schreuders et al., 2018; van Duijvenvoorde et al., 2014; van Duijvenvoorde, Peters, Braams, & Crone, 2016). Research on temporal discounting has shown that adolescents show a preference for immediate monetary rewards and display a high level of discounting, which decreases steadily with age (de Water, Cillessen, & Scheres, 2014; Steinberg et al., 2009) and has also been specifically linked to mesolimbic dopamine functioning (Kayser, Allen, Navarro-Cebrian, Mitchell, & Fields, 2012; Smith et al., 2016). While curiosity has been studied across many age groups, including late childhood and adolescence (Gruber & Fandakova, 2019; Walin, O'Grady, & Xu, 2016), no research has investigated whether it shows a similar trajectory from adolescence into adulthood as reward-sensitivity.

If curiosity can be fully understood as a form of reward seeking, then decreased sensitivity to reward should predict decreased curiosity across the lifespan. However, experimental support for this hypothesis is lacking, and it is important to consider other possible aspects of curiosity that may provide different explanations for the relationship between curiosity and age.

One of the most influential theories of curiosity is Loewenstein's Information Gap Theory, which proposes that curiosity arises when we detect a gap between what we currently know and what we could know (Loewenstein, 1994). While filling gaps is innately rewarding, Loewenstein argues that initial knowledge is key to detecting a gap, and the more knowledge one has about a topic, the more likely they are to be curious about missing information. This was recently tested by Wade and Kidd (2019), who found that curiosity for trivia was predicted by learners' subjective feelings of knowledge about a topic. While most cognitive abilities decline with age, semantic memory remains relatively intact and general knowledge accumulates across the lifespan (Metcalfe, Casal-Roscum, Radin, & Friedman, 2015; Park et al., 2002; Park & Reuter-Lorenz, 2009). Older adults have been shown to use intact semantic memory and prior knowledge to compensate for other deficits (Brashier, Umanath, Cabeza, & Marsh, 2017; Umanath & Marsh, 2014a). This framework makes a different prediction about how curiosity should change with age. If existing knowledge drives us to seek new information, then curiosity may increase across the lifespan.

Measuring Curiosity

It is difficult to ask questions about how curiosity works and how it may change across the lifespan without a clear operationalization of what exactly curiosity is. A large body of literature examined this question by assuming that curiosity is a trait, and measuring a person's tendency to be curious across a variety of situations (for example, Kashdan et al., 2009; Litman, 2008; Naylor, 1981; Spielberger, Jacobs, Crane, & Russell, 1979). A second level of analysis focuses on transient states of curiosity which arise in response to specific stimuli or environmental factors (Grossnickle, 2016). States of curiosity are then measured in many different ways. Explicit measures can include rating one's level of curiosity on a scale (Gruber et al., 2014; McGillivray et al., 2015), or choosing to make an action in order to gain information, like waiting (Kang et al., 2009; Marvin & Shohamy, 2016) or taking a risky gamble (Lau, Ozono, Kuratomi, Komiya, & Murayama, 2018).

Most of the studies on the relationship between curiosity and reward have taken this approach, focusing on the target of curiosity as a single piece of information that can be obtained, like the answer to a trivia question. However, there are other behavioral studies of curiosity that examine it as a more open, exploratory process. The developmental literature often uses these to study how children investigate ambiguity and uncertainty in causal structures (e.g. Schulz & Bonawitz, 2007; van Schijndel et al., 2018). Studies in adults have also used measures of open-ended visual exploration, such as free-viewing images, to study curiosity (Gross, Araujo, Zedelius, & Schooler, 2019; Hoppe, Loetscher, Morey, & Bulling, 2015; Risko, Anderson, Lanthier, & Kingstone, 2012). In these studies, eye movement patterns can shed light on implicit information-seeking strategies based on where people look and how much time they spend exploring. An important question for curiosity research is whether all of these conceptualizations of curiosity reflect the same underlying construct. Most studies use only one approach, making it difficult to know how different information-seeking behaviors relate to each other and, if they differ, how subsets of measures might cluster together.

Overview of the dissertation

In this dissertation, I will present the results of a series of studies exploring the relationship between curiosity, information seeking and reward. Across all three chapters, I investigated the consequences of curiosity for behavior and its relationship to reward sensitivity and learning. I took advantage of the well-characterized age-related changes in reward processing and dopaminergic functioning across the lifespan to probe the relationship between curiosity and reward. At the same time, I used a combination of well-established curiosity paradigms, a novel exploration task, and individual differences measures to understand the variety of behaviors that fall under the umbrella of curiosity. By studying how these behaviors relate to one another, and how they each change with age, I was able to investigate the ways in which curiosity exerts an effect on behavior and how it drives learning.

Chapter 1 describes two studies that test how curiosity-guided behaviors (choices and memory) change with healthy aging. We tested healthy older and younger adults on their willingness to wait for the answers to trivia questions. The first study focused on behavior and found that older adults were more willing to wait for trivia answers than younger adults, and the two age groups were equally likely to remember answers in a subsequent memory test. The second study extended these findings by using fMRI to investigate curiosity-related brain activation. Using the same task, we tested whether older adults would show different patterns of brain activation than younger adults during the trivia task in areas previously linked with reward and semantic memory. Results showed that the two age groups were equally likely to wait for answers and performed similarly on the memory test for trivia. However, older adults performed poorly on a separate memory test for information that did not evoke curiosity, suggesting they experienced a curiosity-related boost in performance on the trivia test. Imaging results also showed a broadly similar pattern of results across older and younger adults, with increased activity in regions related to reward and semantic memory when participants chose to wait for answers compared to when they skipped them. These studies do not provide evidence that curiosity decreases with age, and instead suggest that curiosity may continue to support learning and memory throughout life. Moreover, it may even act to compensate for the commonly found decreases in episodic memory that occur with age.

Chapter 2 examines another aspect of development by testing curiosity during the period from late childhood to early adulthood. In this study, we used the same willingness-to-wait task using trivia questions from Chapter 1, along with a newly developed exploration task which harnesses exploratory eye movements to measure participants' desire to uncover hidden information. These two tasks measure very different behaviors; the exploration task is less verbal, less explicit and does not depend on any existing world knowledge. Combining these two tasks in one study allows us to examine whether there is a single underlying "drive to know" that is common across domains. Results showed a steady increase in both willingness-to-wait and visual exploration with age, accompanied by increases in memory for trivia answers. Again, this is contrary to what might be expected in the reward framework. This chapter considers the possibility that while children and adolescents experience high curiosity, they may not be as able to translate it into goal-directed behavior as adults.

Finally, Chapter 3 describes a study that compares curiosity across multiple domains of measurement, testing how self-reported curiosity may influence behavior to address the broad question of how different forms of curiosity may be reflected in different measurements of the construct. A large online sample of over 700 adults ages 18 to 73 completed behavioral tasks related to willingness to wait for information, reward sensitivity, and memory, along with a suite of trait measures assessing various forms of curiosity and related personality constructs. Results showed that individuals who were high in trait curiosity were more willing to wait for information, and that trait impulsivity predicted decreases in waiting. We also examined age-related changes in state and trait curiosity, and found increases in willingness to wait with age, replicating the results of Chapter 1 and 2, and steady levels of trait curiosity. These findings provide empirical evidence for how the complex relationships between different conceptualizations of curiosity break down into clusters of behavior.

Chapter 1: The effects of aging on curiosity and memory

Everyone knows how it feels to be curious, and curiosity is a fundamental aspect of intrinsically motivated learning. Despite decades of scientific interest in this topic, many open questions remain regarding the cognitive and neural mechanisms by which curiosity drives learning. Recent work has suggested that curiosity may leverage basic reward mechanisms, where desired information is the reward. This framework has not been fully explored, and it is unknown how these reward mechanisms may interact with other cognitive processes to drive information seeking and learning. Many such processes, including reward, are known to change as a function of healthy aging, and studying curiosity across the lifespan may provide insight into its underlying mechanisms.

Recent research on curiosity has framed it as an intrinsic motivation to obtain information, where information can be valuable and rewarding for its own sake (Bromberg-Martin & Hikosaka, 2009; Gottlieb et al., 2013; Kidd & Hayden, 2015). This suggests that the same cognitive and neural mechanisms that support reward processing may contribute to curiosity. Behaviorally, studies have shown that people are willing to trade money and time to gain information that they want (Charpentier et al., 2018; Kang et al., 2009; Marvin & Shohamy, 2016). In the brain, mesolimbic dopaminergic regions that have been linked to reward processing, including the striatum and midbrain, have been shown to be active in curiosity tasks in which the only reward is the answer to a trivia question (Gruber et al., 2014; Kang et al., 2009). Furthermore, anticipatory brain activity in these regions and the hippocampus associated with high curiosity predicted subsequent memory for information (Gruber et al., 2014), providing a link between curiosity and learning.

To test the role of reward processes in curiosity, we can investigate what happens to curiosity when dopaminergic functioning is decreased. Neurobiological research has shown age-related declines in both structure and function in dopaminergic brain areas (Dreher et al., 2008; Sakaki et al., 2018). These declines have been linked to changes in reward processing in learning and decision making tasks, including decreased sensitivity to immediate monetary rewards and difficulty in reward learning tasks involving uncertainty (Eppinger et al., 2011, 2012; Hämmerer & Eppinger, 2012; Nassar et al., 2016; Tripp & Alsop, 1999). If curiosity is dependent on these circuits, then we would expect that curiosity should decrease with age.

However, studies that have looked at the relationship between curiosity and age reveal inconsistent results. One study found decreases in several measures of trait curiosity from early to late adulthood (Robinson, Demetre, & Litman, 2017b), however another found steady levels of trait curiosity with age, both cross-sectionally and in a longitudinal sample (Giambra et al., 1992). Studies using behavioral tasks have not found decreases in curiosity with age. Two studies found that older adults had equal or greater levels of self-reported curiosity for trivia questions compared to younger adults, and that curiosity strongly predicted memory across ages (Galli et al., 2018; McGillivray et al., 2015).

These findings raise questions about the mechanisms underlying curiosity and curiosity-related memory. In particular, they suggest the possibility that other cognitive processes, besides reward, may contribute to curiosity in older age. One hint comes from neuroimaging studies on curiosity that showed that in addition to reward regions, presentation of trivia questions elicits activation in areas linked to semantic knowledge, including the left inferior frontal gyrus (IFG), the parahippocampal gyrus and the dorsomedial prefrontal cortex (Binder, Desai, Graves, & Conant, 2009; Hoffman & Morcom, 2018; Kang et al., 2009). Interestingly, while most cognitive abilities decline with age, semantic memory and other measures of general knowledge have been shown to remain stable or even to increase across the lifespan (Metcalfe et al., 2015; Park et al., 2002; Park & Reuter-Lorenz, 2009; Verhaeghen, 2003). Thus, one possibility is that preserved curiosity in healthy aging could be related to the semantic memory contributions to curiosity-related behaviors.

In particular, Loewenstein (1994) proposed an Information Gap theory of curiosity, in which curiosity results when we detect a gap between what we currently know, and what we could know. A stimulus, such as a trivia question, activates a network of knowledge and highlights a gap in that network. Some piece of initial knowledge is necessary to create a gap, and filling the gap is satisfying and rewarding. However, filling one gap may create others, as new pieces of information highlight additional points of uncertainty (Gottlieb et al., 2013; Loewenstein, 1994). In this view, a larger pool of knowledge leads to more opportunities for curiosity. Since knowledge accumulates with age, a model of curiosity based on knowledge gaps would also predict an increase in curiosity.

The aim of the current work was to better understand the mechanisms underlying curiosity by examining age-related changes in curiosity and its effect on learning and memory. If curiosity is mainly a reward-related process that depends on dopamine transmission, older adults would be expected to show lower levels of curiosity, poorer memory performance for curiosity-inducing material, and less curiosity-related activation in brain regions that are known to be related to reward and to receive dopaminergic input. However, if curiosity makes use of semantic knowledge networks, older adults might be expected to be more prone to curiosity and should show similar, or even better, memory for curiosity-inducing material as younger adults. In addition, we should observe curiosity-related brain activation in areas related to semantic processing.

To test these competing perspectives, we conducted two studies on groups of younger and older adults. While much of the previous behavioral and fMRI research on curiosity has used trivia questions, participants are usually asked to self-report their level of curiosity about the answers. However, we wanted a task which required them to take action to acquire answers, rather than passively receiving them. In both our studies, participants completed a task where they made decisions about how much they wanted to know the answers to a series of trivia questions (adapted from Kang et al., 2009 and Marvin & Shohamy, 2016). Participants had to wait for answers they wanted and were allowed to skip questions they did not want to know the answers to. This task allowed us to quantify curiosity as a willingness to wait. In order to control for differences in willingness to wait in the context of monetary rewards, participants also completed a temporal discounting task. In Study 1, we compared younger and older adults on this task and compared (a) willingness to wait for trivia and (b) memory for answers between the two groups. In Study 2, we recruited a new group of younger and older adults who completed the curiosity task while undergoing an fMRI scan to investigate age-related differences in curiosity-related brain activation.

Study 1

Method

Participants

We aimed to recruit two groups of participants, one between 18 and 35, and one between 50 and 80. For each group, a target sample size of 35 participants was set based on the sample sizes of previous studies on curiosity with similar tasks. (Marvin & Shohamy, 2016;

McGillivray et al., 2015). 35 younger adults (Age=20.4±3.1, range 18 to 34, 17 female) were recruited from introductory psychology courses at Columbia University, and were awarded course credit for their participation. 35 older adults (Age=62.7±8.0, range 52 to 79, 22 female) were recruited from Columbia University and the surrounding community, and were paid $24 for their participation. In general, all participants were highly educated. Among the younger adults, 74% had completed at least some college, and the other 26% had a degree higher than a bachelors. In the older group, 9% completed only high school, 54% completed at least some college, and 37% had a degree higher than a bachelors. The Columbia University IRB approved all study procedures.

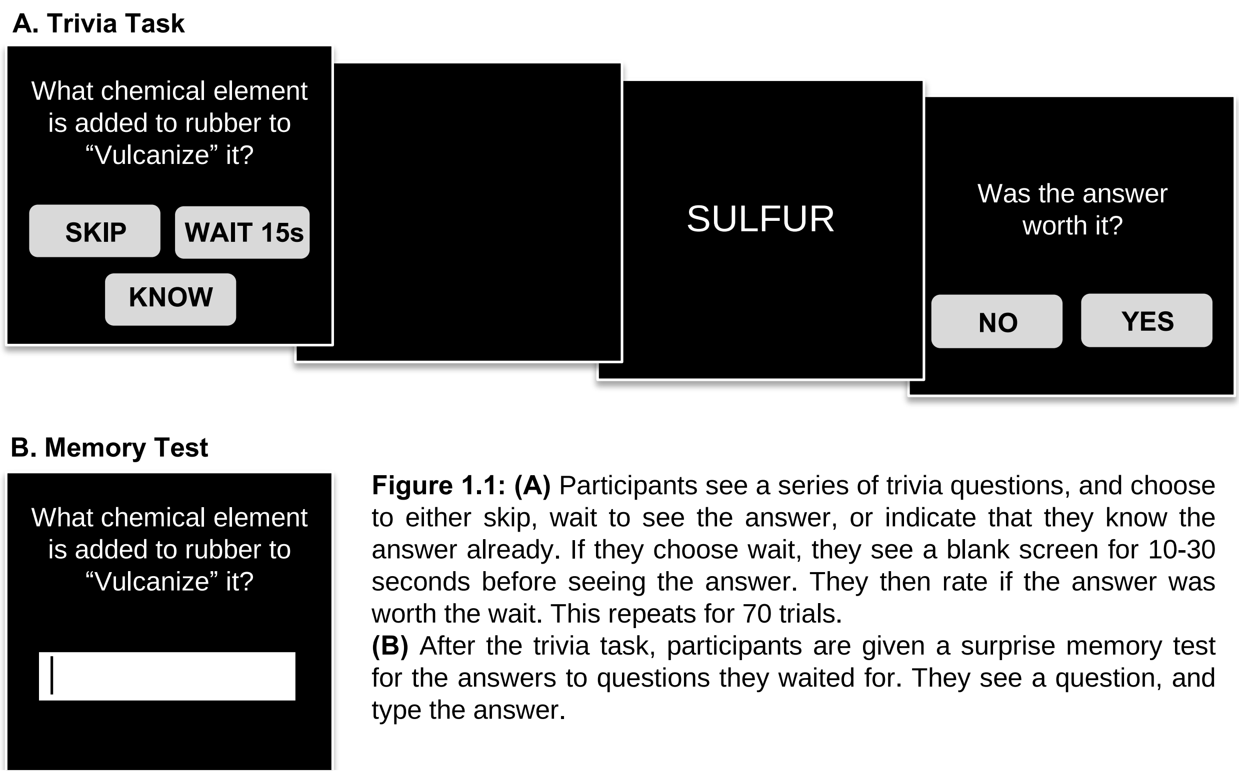

Figure 1.1: (A) Participants see a series of trivia questions, and choose to either skip, wait to see the answer, or indicate that they know the answer already. If they choose wait, they see a blank screen for 10-30 seconds before seeing the answer. They then rate if the answer was worth the wait. This repeats for 70 trials.
(B) After the trivia task, participants are given a surprise memory test for the answers to questions they waited for. They see a question, and type the answer.

Experimental Procedures

Trivia Task: Participants completed a computer trivia task that measured their willingness to wait for information. Trivia questions were displayed one at a time (**Figure 1.1**), and participants had to indicate whether they wanted to know the answer (Wait), skip to the next question without seeing the answer (Skip), or that they already knew the answer (Know). If they chose Wait, they were required to wait up to 30 seconds before viewing the answer. Wait times could be 10, 15, 20, 25 or 30 seconds, and were selected randomly for each trial. The length of the wait was displayed on the screen as they made their choice, and the waiting period began immediately after the decision was made. After the wait time elapsed, the answer appeared on the screen. It was followed by a question asking if the answer was worth waiting for, for which participants selected Yes or No. This was repeated for 70 trials and 70 unique questions. Participants were told that they were free to wait for or skip as many questions as they wanted, but that the entire experimental session would be the same length regardless of how many questions they skipped.

Temporal Discounting: After the trivia task, participants completed a monetary discounting task. They were asked to decide if they would prefer to receive $30 immediately, or a larger amount some time in the future. There were six future amounts ($32, $38, $42, $48, $52 and $58), and six delays (2 months, 4 months, 6 months, 9 months, 1 year and 2 years). The task consisted of 36 trials with the amounts and delays evenly counterbalanced. Participants were told at the start that the decisions were hypothetical, but to make their choices based on what they would want to do if they were real. This task was scored based on the proportion of trials where participants choose the delayed option.

Surprise Memory Test: After a delay for the temporal discounting task and questionnaires, participants were presented with a surprise memory test for the answers they had seen in the trivia task. Questions that each participant waited for were shown on the screen one at a time, and participants were asked to type the answer. This test was untimed. All answers were single words or short phrases. Responses were scored as either correct or incorrect (no partial credit), but participants were not penalized for misspellings or variations in phrasing.

Independent Curiosity Ratings

Questions were selected from a larger database of questions previously rated by a separate group of participants on MTurk (N=800, ages ranging from 18-75). Online participants rated their curiosity about the trivia questions on a continuous scale from 0 ("Not at all curious") to 100 ("Extremely curious"). Each question was rated by between 30 and 60 people. Ratings were then averaged for each question and z-transformed, providing a standard measure of how curious people tended to be about each question. Questions covered a range of topics, including science, history, general knowledge and pop culture.

Analysis

All analyses were conducted using Bayesian modeling techniques. For each task we constructed multilevel models using the brms package in R (Bürkner, 2017) to predict trial-by-trial data. All models used minimally informative priors as recommended by Gelman (2008). Predictors were centered and scaled, and priors were set with Cauchy distributions with mean zero and standard deviations of 10 for intercepts and 2.5 for predictors.

We constructed a multilevel logistic model to predicted the choice to wait for an answer instead of skipping ahead (Know trials removed) based on age group (young or old), wait length, question curiosity scores, and trial number. We also included interaction terms for all pairwise interactions. A second model to predict worth ratings included the same predictors. For the analysis of memory data, we predicted correct vs incorrect memory for answers based on those same predictors, with an additional subject level variable for the total number of items a person waited for. Each model also included random intercepts by participant and by question, and random slopes for the predictor variables and their interactions, as appropriate.

To incorporate the data from the delay discounting task, we took a two-stage approach. Recent work on discounting tasks has used logistic regression to derive individual estimates for the effect of both time delay and reward size on discounting choices (Wileyto, Audrain-McGovern, Epstein, & Lerman, 2004; Young, 2018), rather than calculating a single value of the discounting parameter, *k*. Following the procedure provided by Young (2018), we used multilevel logistic regression to predict now/later choices based on both delay time and reward ratio (later value divided by now value). Random slopes and intercepts are included for each participant, and participant-level coefficients provides individual estimates for the degree of influence each factor had on individual choices. For example, one participant may rely heavily on reward value to make decisions, and ignore the delay, while another might do the opposite. These subject-level coefficients were then used as predictors in the model to predict skipping or waiting on the trivia task.

Results

Willingness to Wait

On average, older adults waited for more questions (M=41.31 questions, sd=18.06) than the younger adults (M=32.66, sd=12.19). The results of the multilevel models showed that, for a given question, older participants were more likely to wait than younger adults, even after controlling for levels of question curiosity and wait length (b = 1.64, 95% CI [0.84, 2.49], **Fig. 1.2A**). There was also a main effect of question curiosity, where all participants were more likely to wait for higher curiosity questions (b = 0.97, 95% CI [0.73, 1.22]) compared to low curiosity questions. There was no interaction between age group and question curiosity, showing that older adults were more likely to wait for both high and low curiosity questions (b = -0.007, 95% CI [-0.31, 0.31]; **Fig. 1.2B**). There were also main effects of wait length and trial number, such that participants were less likely to wait as wait length increased (b = -0.50, 95% CI [-0.63, -0.36]) and less likely to wait in later trials compared to earlier trials (b = -0.26, 95% CI [-0.34, -0.17]). Neither of these predictors interacted with age group (Wait Length: b = -0.10, 95% CI [-0.36, 0.17]; Trial: b = 0.08, 95% CI [-0.10, 0.25]).

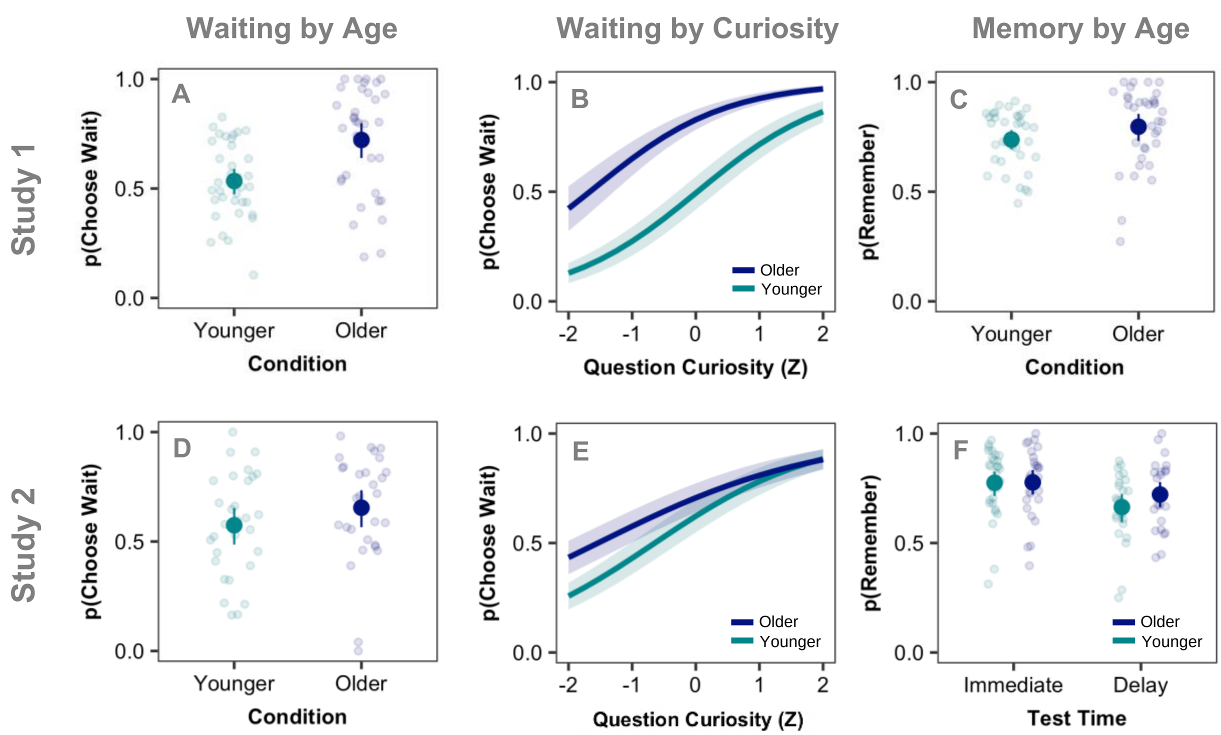

Figure 1.2: **Behavioral Results for Study 1 and Study 2** In Study 1, **(A)** older adults were more likely to wait for answers than younger adults. Small dots show individual proportions for waiting vs skipping (know trials removed). Large dots show group averages with 95% credible intervals. **(B)** The effect of age was seen across levels of question curiosity, which also independently predicted waiting. Lines show model estimates of the probability of waiting, with 95% credible intervals. **(C)** On the subsequent memory test, older adults and younger adults showed similar memory performance. Small dots show individual scores, calculated as the proportion of answers remembered. Large dots show group averages. In Study 2, **(D)** older adults and younger adults waited for a similar proportion of questions, although the group average for older adults was slightly higher. **(E)** As in Study 1, question curiosity positively predicted the probability of waiting. **(F)** Older and younger adults performed similarly on the immediate test, but an interaction between time and age group showed that older adults forgot fewer answers than younger adults during the delay before the second test one week later.

To test whether an individual's general tendency to delay gratification for rewards was related to their willingness to wait for information, we ran a second version of the model with the measures of sensitivity to reward and delay derived from the temporal discounting task as subject-level predictors. Neither of these measures predicted willingness to wait on the trivia task (Delay: b = -0.25, 95% CI [-0.97, 0.45]; Reward: b = 0.24, 95% CI [-0.47, 0.92]. Separately, we tested the correlation between the proportion of trials that the participant waited for in the trivia task and proportion of trials they chose the delayed option on the discounting task, and found no relationship (r=0.08, 95% CI [-0.14 0.32]. While null results are difficult to interpret, this suggests that willingness to wait for information is not simply a byproduct of one's patience and willingness to delay gratification for other rewards. We also found no evidence that older adults waited for more trials on the discounting task than younger adults (*b* = 0.07, 95% CI [-0.07, 0.20]).

Judgments of worth

Participants generally rated the answers they waited for to be "worth the wait", answering yes to an average of 79% of answers seen (SD=13%). Older adults were even more likely than younger adults to answer "yes", rating an average of 84% (SD=11) of questions as worth it, compared to 74% (SD=12) for younger adults. In the logistic model, older adults had a higher probability of rating an answer as worth the wait than younger adults (b = 0.88, 95% CI [0.25, 1.51]). In addition, the probability of answering "yes" increased with question curiosity b = 0.42, 95% CI [0.14, 0.71]), and decreased with wait length (b = -0.24, 95% CI [-0.40, -0.08]).

Memory for Answers

In the memory test, participants remembered an average of 77% of the answers (SD= 16). Older participants remembered more answers (M=79.66±18.1), on average, than younger participants (M=73.77±13.17). On a trial-by-trial basis, older participants were more likely to remember an answer than younger participants (b = 0.71, 95% CI [0.008, 1.43]; **Fig. 1.2C**), after controlling for question curiosity, wait length, and the total number of answers to be remembered. Answers to high curiosity questions were remembered better than answers to low curiosity questions (b = 0.41, 95% CI [0.04, 0.78]). The model showed weak evidence of an interaction between age group and question curiosity, such that older adults were more likely than younger adults to remember the low curiosity questions, but there was a large amount of uncertainty around this estimate (b = -0.34, 95% CI [-0.78, 0.11]). There was no evidence that wait length impacted memory (b = -0.07, 95% CI [-0.23, 0.08].

Existing Knowledge

We also wanted to test for differences between the two groups on how many questions they reported knowing the answers to already. On average, older adults reported knowing 13.83 (sd=10.95) answers, compared to 8.54 for younger adults (sd=8.1). However, there was a high degree of variability in the number of answers known, and a model predicting the number known for each participant did not indicate strong evidence for a difference between age groups b = 3.67, 95% CI [-0.37, 8.49]. That said, it is worth noting that in this study we did not test whether participants actually knew the answers if they chose Know, as only Wait questions were included in the subsequent test.

Interim Summary

The results of Study 1 showed that older adults were more curious than younger adults. They were more willing to wait for answers to trivia questions, and this difference was not explained by differences on the temporal discounting task measuring general willingness to wait for rewards. In addition, higher question curiosity predicted memory performance for both younger and older adults, and the two age groups performed similarly on the memory test. Given that memory generally declines with age, this equivalent performance is surprising, although it is in line with previous findings on the effect of curiosity on memory in older adults (McGillivray et al., 2015). We sought to replicate and expand these findings in Study 2.

Study 2

In Study 2, we recruited new groups of younger and older adults to perform the curiosity task while undergoing fMRI scanning. This allowed us to examine curiosity-related brain activity across ages. We also included additional control measures for time perception, episodic memory, and working memory, along with a new discounting task, to test for differences between the groups that might account for differences in waiting behavior.

Method

Participants

We aimed to collect usable data for 30 older participants and 30 younger participants, for a total of 60. For this study, we restricted the age range for the older adults to 65-80. Participants were screened over the phone for their eligibility to complete an MRI scan. In all, 74 participants completed some or all of the study. Fourteen of these (7 older adults and 7 younger adults) were excluded from analysis for technical problems with the scanner (N=3), incidental findings (N=1), low MMSE score (N=1), having completed a previous, similar study (N=1), or because they were unable to complete the scan or follow task directions (N=8). This left 30 younger adults (Age=23.2±4.4, range 18 to 34, 17 female) and 30 older adults (Age=70.10±4.0, range 65 to 80, 20 female). As in Study 1, the sample had a high level of education, having either completed at least some college (80% of younger adults, 46% of older adults), or completed education beyond college (20% of younger adults, 54% of older adults). Participants were paid $80 for their participation. All participants provided written informed consent and all procedures were approved by the Columbia University IRB.

Experimental Procedures

Participants completed a 3-hour session, which included both behavioral and MRI tasks. Upon arrival, they completed the consent procedures, followed by questionnaires, neuropsychological tests, control tasks (see below) and a practice task for the scanner consisting of instructions and three trials of the trivia task and three trials of the discounting task. They then proceeded to the scanner to complete the trivia task and discounting task. After the scan, they returned to the lab for the memory test and debriefing.

Trivia Task: The trivia task was the same as in Study 1, except for the following changes. Rather than a set number of questions, we changed the task so that it would have a set duration. The task was divided into four functional MRI runs, each 7 minutes long. The task would continually provide new questions until the time limit was reached, resulting in different number of trials per subject. Second, to fit in more trials, wait times were set to 8, 12, 16 or 20 seconds. Finally, the Worth question was changed from a yes/no question to a five-point rating scale. Participants made responses using a five-button box placed in their right hand.

Temporal Discounting: The discounting task also took place in the scanner, across two seven-minute functional runs. A new version of the task was used for study 2 to accommodate shorter wait times and smaller amounts, to be more in line with previous studies used in the scanner (Eppinger et al., 2012; McClure, Laibson, Loewenstein, & Cohen, 2004; Samanez-Larkin et al., 2011). The monetary value today was randomly drawn for each trial from a normal distribution with a mean of 20 dollars and a standard deviation of 5. The later amount was then calculated as either 5, 10, 15, 25, 35 or 50% larger than the today amount, at time delays of 1, 2, 3, 4, 5, or 6 weeks. The trial types were counterbalanced within each run so that all reward ratios occurred for all delay lengths, resulting in 36 trials per run, and a total of 72 trials total. The task was incentive compatible, and one trial was selected at random to be paid out via Amazon giftcard.

Memory for Trivia: Participants completed the same trivia memory test as in Study 1. One at a time, they were shown trivia questions they had waited for and asked to type the answers. This time, questions they claimed to know were also tested. Seven days after the experimental session, participants were emailed a link to a survey with a second memory test. This consisted of only the waited questions. Participants were told at the end of the lab session that they would be asked to complete a survey, but not that it would contain a memory test. Most participants successfully completed the second memory test (N=25 Younger, N=24 Older). Although they were asked to do it as soon as possible, many participants waited longer to complete the test (Younger M=8.7±5.1 days; Older M=9.7±4.4 days).

Face Name Associative Memory Exam: To test memory for information learned in a task which we did not expect to elicit curiosity, participants completed a version of the Face Name Associative Memory Exam (FNAME; Papp et al., 2014). This task tests associative memory by having participants learn pairings between faces and their names and occupations. Correct pairings are only learned once, but then are tested multiple times at different time delays. Testing consists of showing the face, and asking participants to generate the correct name and occupation. We chose this task because it requires cued recall of information, like in the trivia task, but is not designed to evoke curiosity. This task has also been validated in older adults, and shows steady decreases in performance with age (Amariglio et al., 2012). Participants completed this task before the scan, and then were tested on the pairings after the scan at the same time as the trivia memory test, and again in the online memory test one week later.

Duration Task: Previous literature has suggested potential age-related changes in time perception, specifically that older adults may have a faster internal clock than younger adults when judging short durations (Carrasco, Bernal, & Redolat, 2001; Coelho et al., 2004). If wait times in the trivia task "feel" shorter to older participants, they may be more willing to wait than younger participants, regardless of curiosity. To test this, we including a control task where participants judged the duration of stimuli, adapted from an existing time perception task (Akdoğan & Balci, 2017). A colored square appeared on the screen and then disappeared. Participants would then try to recreate the duration of the square presentation by pressing a button and releasing it when the correct amount of time had passed. The task of consisted of 40 trials divided into two counterbalanced blocks with target durations of either 8 or 16 seconds. All trials in a block had the same duration, but participants were not told this. They were instructed not to count, tap, look at a watch or use any other method to try to keep track of the time.

Other tests: To test for baseline levels of cognitive functioning, we administered the Mini Mental State Exam (MMSE, Folstein, Folstein, & Mchugh, 1975) to all participants. Participants who scored less than 24 out of 30 were excluded from the analysis. We also administered the forward and backward digit span test to assess levels of working memory (Wechsler, 1955).

Behavioral Analysis

Behavioral analyses were conducted using Bayesian modeling techniques in the same manner as Study 1. Logistic regression models were the same as those used in Study 1, except for the model predicting memory. Since we had two memory tests (immediate and delay), we included both in the same model with an additional categorical predictor for test time, and interactions between test time and age, question curiosity and wait length.

Imaging Acquisition

MRI data were collected on a 3-T Siemens Magnetom Prisma scanner with a 64-channel head coil. First, T1-weighted structural images (1x1x1 mm) were acquired with a magnetization-prepared rapid acquisition gradient-echo sequence (MPRAGE). There were six functional runs, four for the curiosity task and two for the discounting task. The runs for the curiosity task always occurred first. Each run was approximately 7 minutes long. Functional images were obtained with a multiband echo-planar imaging (EPI) sequence (repetition time = 1.5 s, echo time = 30 ms, flip angle = 70°, acceleration factor = 3, voxel size = 2x2x2mm, FOV=192mm, 69 axial slices acquired in an interleaved order). Field maps were collected to aid registration.

Imaging Preprocessing

Results included in this manuscript come from preprocessing performed using FMRIPREP version 1.1.4 (Esteban et al., 2018), a Nipype (K. Gorgolewski et al., 2011; K. J. Gorgolewski et al., 2017) based tool. Each T1w (T1-weighted) volume was corrected for INU (intensity non-uniformity) using N4BiasFieldCorrection v2.1.0 (Tustison et al., 2010) and skull-stripped using antsBrainExtraction.sh v2.1.0 (using the OASIS template). Spatial normalization to the ICBM 152 Nonlinear Asymmetrical template version 2009c (Fonov, Evans, McKinstry, Almli, & Collins, 2009) was performed through nonlinear registration with the antsRegistration tool of ANTs v2.1.0 (Avants, Epstein, Grossman, & Gee, 2008), using brain-extracted versions of both T1w volume and template. Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and gray-matter (GM) was performed on the brain-extracted T1w using fast (Zhang, Brady, & Smith, 2001).

Functional data was motion corrected using mcflirt in FSL v5.0.9 (Jenkinson, Bannister, Brady, & Smith, 2002). Distortion correction was performed using an implementation of the TOPUP technique (Andersson, Skare, & Ashburner, 2003) using 3dQwarp in AFNI v16.2.07 (Cox, 1996). This was followed by co-registration to the corresponding T1w using boundary-based registration (Greve & Fischl, 2009) with six degrees of freedom, using flirt (FSL). Motion correcting transformations, field distortion correcting warp, BOLD-to-T1w transformation and T1w-to-template (MNI) warp were concatenated and applied in a single step using antsApplyTransforms (ANTs v2.1.0) using Lanczos interpolation.

Physiological noise regressors were extracted applying CompCor (Behzadi, Restom, Liau, & Liu, 2007). Principal components were estimated for the two CompCor variants: temporal (tCompCor) and anatomical (aCompCor). A mask to exclude signal with cortical origin was obtained by eroding the brain mask, ensuring it only contained subcortical structures. Six tCompCor components were then calculated including only the top 5% variable voxels within that subcortical mask. For aCompCor, six components were calculated within the intersection of the subcortical mask and the union of CSF and WM masks calculated in T1w space, after their projection to the native space of each functional run. Frame-wise displacement (Power et al., 2014) was calculated for each functional run using the implementation of Nipype.

Imaging Analysis

Our general linear model (GLM) analysis was carried out using FSL's FEAT tools. The model for the curiosity task included three event types. The decision period, when participants read the question and decided whether to indicate wait, skip or know, was modeled as a boxcar function beginning at the onset of the question and continuing until the participant made a response, resulting in a variable epoch. This technique was shown to capture more variance in the BOLD response during decision making tasks than models that either ignored reaction time or treated it as a separate parametric regression (Grinband, Wager, Lindquist, Ferrera, & Hirsch, 2008). The second time period was the four seconds when the answer appeared. The third period was after the answer when participants rated whether the answer was worth waiting for. This was also modeled using a variable epoch starting at the presentation of the scale and ending when the participant made their response. Motion regressors generated by fmriprep were included in the model as regressors of no interest.

A first level GLM analysis was run separately for each participant in each run of the curiosity task, followed by a second-level analysis combining across runs, and a third-level analysis combining across participants. We created contrasts of interest for the decision period for choices of wait vs skip, choices to wait vs know, and choices of skip vs know. For the answer period, we also created a contrast for answers that were remembered vs forgotten at the first memory test. Since this task allows participants to freely choose how to respond to each trivia question, there were some runs which did not include all contrasts (e.g. a subject did not choose "know" for any question). In these runs, subjects were removed from the contrasts they were missing, but all other contrasts were retained. As a result, each contrast had a slightly different number of subjects and runs. The same was true for the remembered > forgotten contrast, as memory performance was generally very high and some runs had no forgotten items. To examine group differences between the older adults and younger adults, we included age group in the third of level analysis, with regressors for each group alone, the two groups contrasted against each other (young > old and old > young), and all subjects combined.

For whole brain analyses across subjects, clusters were thresholded at a level of $Z>2.3$, with a cluster-corrected significance level of $p<.05$. Tables were created using FSL's "Cluster" command on the resulting maps. Labels were determined using the Harvard-Oxford structural atlas and other relevant atlases.

As we were particularly interested in the effects of curiosity in areas of the brain related to reward and semantic processing, we performed an ROI analysis using the automated meta-analyses tools from Neurosynth (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011), following the example of Cohen, Rissman, Suthana, Castel, & Knowlton, (2016). We used Neurosynth to generate separate maps of brain regions linked to the terms "reward" and "semantic". The resulting map included all voxels that were more likely to be activated by the target terms than would be expected by chance, (corrected FDR threshold of $p<.01$). To control the spatial extent of the maps, we applied an additional threshold of $z>5.2$ (Cohen et al., 2016). The final reward map contained 5099 voxels with data from 922 studies, and consisted of clusters in the striatum, midbrain and prefrontal cortex. The semantic map contained 6342 voxels with data from 1031 studies, and consisted of clusters in the left inferior frontal gyrus, left lateral temporal cortex, angular gyrus and dorsomedial prefrontal cortex. Both of these maps were used to mask the contrast wait > skip. We also created a third ROI map using Neurosynth and the term "episodic memory". The resulting map included data from 332 studies and included 3148 voxels in clusters in the hippocampus and parahippocampal gyrus and the precuneus. This ROI was used to mask the contrast remembered > forgotten.

Results

Willingness to wait

Across the entire task, older and younger adults waited for roughly the same number of questions (Older: M=39.6, sd=13.18); Younger: M=41.37, sd=9.21). The multilevel model predicting choices to wait or skip showed no main effect for the difference between age groups (b = 0.39, 95% CI [-0.51, 1.28]; **Fig. 1.2D**). As in study 1, participants were more likely to wait for high curiosity questions (b = 0.69, 95% CI [0.54, 0.84]; **Fig. 1.2E**), and less likely to wait if the wait time was long (b = -0.34, 95% CI [-0.46, -0.21]). While there was no overall difference between the age groups on waiting behavior, two interactions hint at differences between these groups. Older adults were less sensitive to the wait time than younger adults, such that they were equally willing to wait when the wait time was long compared to when it was short (b = 0.49, 95% CI [0.24, 0.75]). Older adults were also less sensitive to the length of the task. Early in the task, older and younger adults were equally likely to wait for answers, but younger adults waited less as time went on while older adults showed a much smaller decline (b = 0.67, 95% CI [0.46, 0.87]).

To test if the groups' curiosity driven behavior could be explained by age-related changes in patience and willingness to wait in general, we constructed a second model with subject level predictors derived from the temporal discounting task representing sensitivity to changes in delays and rewards. As in Study 1, these measures did not predict willingness to wait for trivia (Delay: b = -0.19, 95% CI [-0.68, 0.29]; Reward: b = -0.01, 95% CI [-0.49, 0.47]. Also, as in Study 1, older adults did not make a greater proportion of later choices than younger adults *b* = 0.07, 95% CI [-0.07, 0.21])

Judgements of Worth

We also tested whether judgements of worth varied between the two age groups. While the effect was in the same direction as in Study 1, with older adults showing higher worth judgements, the effect had a high level of uncertainty and the 95% credible interval included zero (b = 0.26, 95% CI [-0.03, 0.54]). As before, question curiosity positively predicted worth judgements (b = 0.21, 95% CI [0.14, 0.28]). Worth ratings did not decrease with wait length (b = 0.01, 95% CI [-0.04, 0.07]).

Memory

We tested memory for answers on the day of the scan, and again one week later. Overall, memory performance was very high at both time points (Immediate: *M*=77.59%, *sd*=15.5; Delay: *M*=69.33%, *sd*=15.89). To test the effects of age and curiosity on subsequent memory, we constructed a model predicting whether answers would be remembered or forgotten based on age group, question curiosity, wait length, and test time. As in study 1, answers to high curiosity questions were remembered better than low curiosity questions (b = 0.68, 95% CI [0.39, 0.98]). Performance was lower after the delay (b = -0.54, 95% CI [-0.73, -0.35]), but the effect of curiosity was found for both time points (b = -0.02, 95% CI [-0.23, 0.18]). There was no overall main effect of age group (b = 0.34, 95% CI [-0.43, 1.07]). However, there was an interaction between age and time, where younger adults forgot more answers after the delay, while older adults forgot relatively few answers (b = 0.48, 95% CI [0.11, 0.86]; **Fig. 1.2F**). Additionally, there was an interaction between age group and question curiosity, such that both groups remembered high curiosity answers equally well, but older adults remembered more low curiosity answers (b = -0.41, 95% CI [-0.80, -0.02]).

In general, memory is expected to decline with age, so it is surprising to see older adults performing as well as younger ones. To test whether these effects were unique to curiosity, or whether our sample of older adults happened to have high levels of memory performance across multiple domains, we tested two other memory measures. On the digit span test, which measures working memory, older adults performed worse than the younger adults (b = -1.29, 95% CI [-2.43, -0.13]). On the Face Name Associative Memory Exam, older adults were less likely than younger adults to correctly recall the names and occupations of the different faces (b = -0.87, 95% CI [-1.43, -0.31]) on both the immediate test and the one-week follow-up. Performance for both groups decreased from time one to time 2 (b = -1.16, 95% CI [-1.35, -0.97]), but unlike the trivia test, older adults and younger adults showed similar decreases (b = -0.17, 95% CI [-0.52, 0.19]).

Existing Knowledge

To test for differences between age groups on how many questions they reported knowing the answers to, we looked at trials where participants chose "Know". Older adults reported knowing 20.07 (sd=17.77) answers, compared to 17.53 for younger adults (sd=15.69), but again variability was high and the model did not indicate strong evidence for a difference between age groups *b* = 0.95, 95% CI [-4.07, 6.95]. Unlike Study 1, the memory test on the day of the scan included questions where participants had chosen Know. In general, participants did not actually know as many questions as they claimed to know (M=37.7%, sd=19.85%). There was no difference between the age groups in the proportion of these questions that they actually knew (*b* = 0.05, 95% CI [-0.05, 0.16]).

Time Perception

In the time perception task, we tested whether older and younger adults showed different biases in estimating time intervals similar to those used in the trivia task. We found no differences between the age groups on the average deviation from the target duration (b = 0.04, 95% CI [-0.92, 0.98]).

Imaging Results

We first examined BOLD activity during the question period, comparing trials for which participants chose to wait vs. those for which they chose to skip, in each age group separately We expected that this contrast would reflect curiosity-related activation.

In the younger adults, a whole-brain analysis showed a diffuse pattern of activation. We observed significant effects of wait>skip in the inferior frontal gyrus, middle frontal gyrus, caudate, lingual gyrus and cerebellum, regions that overlap with those reported by Kang et al. (2009) for high vs. low self-reported curiosity. In addition, the younger adults showed distinct clusters of activation in the ventromedial prefrontal cortex and the medial temporal cortex. A parallel analysis in the older adults revealed a similar pattern, including the left IFG and bilateral MFG, although they did not show any significant activation in the VMPFC or striatum. In direct a contrast between younger and older adults in the whole brain, younger adults showed greater activation in a number of regions, including the medial prefrontal cortex (see **Supplementary Table 1.1** for all regions showing a significant group difference). No regions showed significantly higher activation for older adults compared to younger ones.

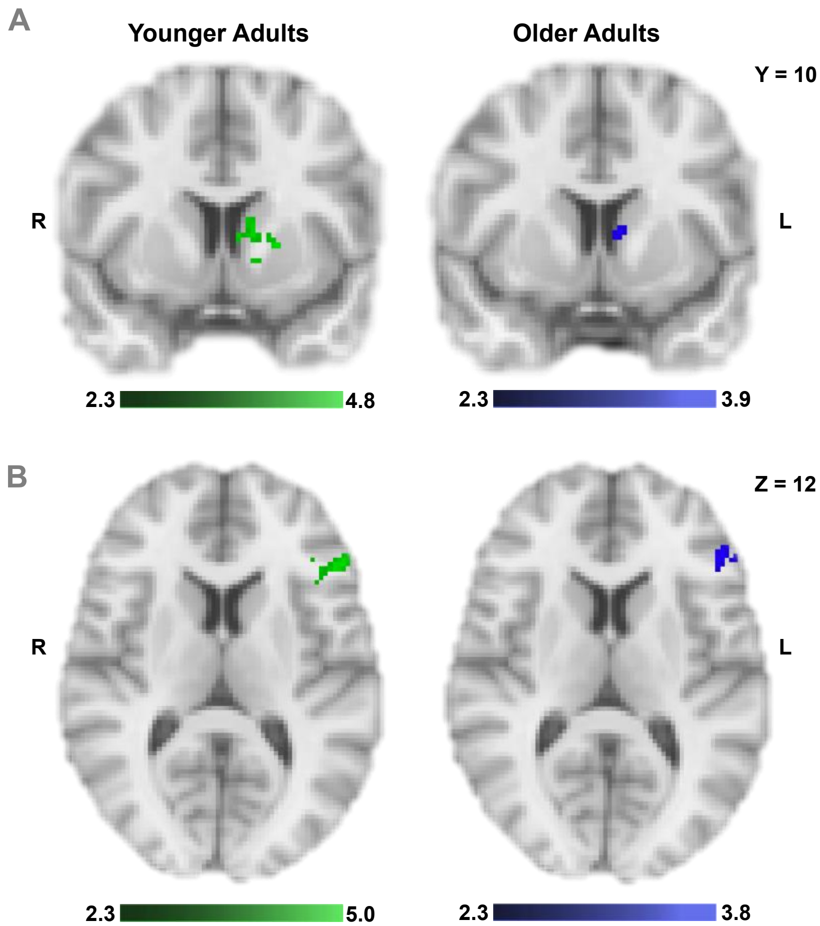

Figure 1.3: **BOLD activity that is greater when participants decide to wait for the answer to a trivia question vs. when then decide to skip it. (A)** During the period when the question was presented, both younger and older adults showed increased activation in the left caudate nucleus when they chose to wait compared to when they chose to skip. Image shows activation map after masking with “reward” ROI. **(B)** In the same period, with the “semantic” ROI mask, younger and older adults showed similar patterns of activation in the left inferior frontal gyrus (IFG).

In order to further investigate the role of reward-related regions, we conducted an ROI analysis using a mask derived from Neurosynth for the term “reward”. Both younger and older adults showed clusters of activation in the left caudate when they chose to wait rather than skip

(**Fig 1.3A**). Younger adults additionally showed activation in the ventral tegmental area (VTA) and the ventromedial prefrontal cortex, however direct contrasts showed no areas within this ROI with significantly higher activation for younger vs older adults or vice versa. Regions and peak coordinates for each group are shown in **Table 1.1**.

Table 1.1: Regions showing greater activation for Wait vs. Skip Choices in Reward ROI Analysis

Region	Voxels	z-stat	X	Y	Z
Younger Adults					
L Caudate	158	3.83	-6	6	2
R Ventral Tegmental Area	41	3.37	4	-14	-8
L Ventromedial Prefrontal Cortex	41	4.73	-2	40	-14
Older Adults					
L Caudate	50	3.89	-6	6	4

Coordinates in MNI Space. No clusters survived correction for contrasts of Older > Younger and Younger > Older.

In the second ROI analysis, we masked the Wait > Skip activation based on a mask from Neurosynth for the term "semantic". Younger adults showed increased activation for wait vs skip in the left IFG, two regions of the left temporal lobe, the left lateral prefrontal cortex and the left lateral occipital cortex. Older adults showed increased activation in two clusters within the IFG, which overlapped with those found in the younger adults **(Fig 1.3B).** In direct contrasts, no regions within the ROI showed higher activation for older vs younger adults, but younger adults did show greater activity than older adults in the lateral prefrontal cortex and occipital cortex. Regions and peak coordinates are shown in **Table 1.2**.

We next examined whether BOLD activity during the answer period differed between answers that were later remembered vs., those that were later forgotten, first examining younger

Table 1.2: Regions showing greater activation for Wait vs Skip Choices in Semantic ROI Analysis

Region	Voxels	z-stat	X	Y	Z
Younger Adults					
L Inferior Frontal Gyrus, pars opercularis	363	4.49	-38	14	30
L Middle Temporal Gyrus, temporooccipital	244	5.05	-56	-50	-10
L Lateral Prefrontal Cortex	117	4.63	-42	40	-14
L Middle Temporal Gyrus, Anterior	88	3.76	-58	-14	-14
L Lateral Occipital Cortex	50	3.62	-56	-62	26
L Lateral Occipital Cortex	47	3.94	-34	-68	44
Older Adults					
L Inferior Frontal Gyrus, pars opercularis	116	3.73	-52	10	18
L Inferior Frontal Gyrus, pars triangularis	72	3.52	-50	38	10
Younger > Older					
L Lateral Prefrontal Cortex	63	3.40	-46	28	-8
L Lateral Occipital Cortex	61	3.75	-46	-60	22

Coordinates in MNI Space. No clusters survived correction for contrast of Older > Younger.

and older adults separately. The whole brain analysis for younger adults showed multiple regions with higher activation for remembered vs forgotten items, including the lateral prefrontal cortex, left lateral temporal cortex, precuneus and caudate. Older adults showed activation in the ventromedial prefrontal cortex and right hippocampus, but not the caudate. Whole brain contrasts for Young > Old did not show any significant differences, while the contrast for Old > Young showed series of small clusters in the occipital cortex. Whole brain results for Remembered > Forgotten are shown in **Supplementary Table 1.2**.

We then used a Neurosynth mask for the term "episodic memory" to examine patterns of activation in regions specifically related to memory. Younger adults showed a cluster of activation in the precuneus, while older adults showed a cluster in the right hippocampus. Unlike in previous studies on curiosity, participants were only shown the answers to questions they chose to wait for, reducing the number of trials available for the analysis. Furthermore, since memory performance was high, some runs did not have "forgotten" trials for some subjects. To further investigate activation in these regions, we looked at the remembered > forgotten contrast with all subjects together. This showed bilateral activation of the hippocampus, as well as a significant cluster in the precuneus **(Table 1.3).**

Table 1.3: Regions showing greater activation for Remembered vs. Forgotten Answers in Memory ROI Analysis

Region	Voxels	z-stat	X	Y	Z
Younger Adults					
L Precuneus	76	4.63	-4	-56	22
Older Adults					
R Hippocampus	52	3.69	22	-20	-16
All Subjects					
L Precuneus	119	5.40	-2	-56	14
R Hippocampus	42	3.73	22	-20	-16
L Hippocampus	38	4.03	-24	-22	-18

Coordinates in MNI Space. No clusters survived correction for contrasts of Older > Younger and Younger > Older.

Discussion

Across two studies, we sought to measure changes in curiosity related to healthy aging. We found evidence for equal or greater curiosity in older adults compared to younger adults. In Study 1, older adults were more willing to wait for answers than younger adults. In Study 2, the younger and older groups waited at roughly the same rate overall, but older adults were less sensitive to factors like wait length compared with younger adults. In both studies, both age groups were sensitive to the curiosity levels of the questions, showing more willingness to wait and improved memory for the highest curiosity questions.

The imaging results of Study 2 focused on activation when participants expressed curiosity by choosing to wait for answers. While the whole brain analysis did show more areas of activation for younger adults during the period, but the ROI analyses of reward and semantic regions showed broadly similar patterns of activation for younger and older adults Given that we found no behavioral differences between the age groups in Study 2, the lack of age-related differences in brain activity in these key regions may not seem surprising. However, these findings go against the prediction that age related decreases in curiosity are driven by declines in mesolimbic dopaminergic regions. Instead, the pattern of results during the decision to wait instead of skip sheds light on the contributions of both reward processing and knowledge for curiosity.

The ROI analysis of the reward network replicated findings from previous studies showing that mesolimbic dopaminergic regions are active in response to curiosity in trivia tasks (Gruber et al., 2014; Kang et al., 2009). This analysis showed increased activation in the left caudate in both younger and older adults when participants chose to wait for an answer. In previous research this region has been linked to reward anticipation, and this fits an interpretation where information (the answer) serves as a reward that participants choose to pursue by waiting. There were no significant differences between younger and older adults in these regions, although younger adults did show additional activation in the midbrain and VMPFC.

The ROI analysis of the semantic network showed overlapping clusters of activation in the left IFG. Previous work on semantic processing suggests that this region is related to semantic control, involved in activating relevant and context-appropriate information (Hoffman & Morcom, 2018). In tasks involving trivia, recalling contextual details is important for understanding the questions and assessing if one already knows the answer. The fact that this area is more active when participants choose to wait instead of skip suggests that curiosity specifically requires accessing this stored knowledge. The semantic analysis showed that younger adults have more overall areas of activation, and several regions where activation was higher for younger than older adults. This is in line with research on semantic processing that has found that with age, semantic activation in the brain becomes more diffuse – spreading out to include more regions, but with weaker levels of activation at the peaks. Semantic processing in older adults is less constrained to the left lateralized regions of the temporal and frontal cortices, and instead spreads into the right hemisphere and to other regions with less functional specialization (Hoffman & Morcom, 2018). Overall, the fMRI results during the decision period of the task show little evidence for fundamental differences in the way younger and older adults process curiosity.

Curiosity plays an essential role in learning, and has been repeatedly shown to improve memory for information we are curious about (Galli et al., 2018; Gruber et al., 2014; Kang et al., 2009; McGillivray et al., 2015; Walin et al., 2016). In both studies, participants in both age groups showed a curiosity related memory boost, remembering the answers to high curiosity questions better than low curiosity questions, both in immediate and delayed tests. This replicates previous studies showing that levels of curiosity and interest predict memory in older adults (Galli et al., 2018; McGillivray et al., 2015). This equal memory performance is surprising given the well-known memory deficits that accompany aging. We demonstrated that this effect was specific to curiosity, as the older adults performed worse than younger adults on the separate non-curiosity memory task and the working memory test. This finding rules out the possibility that older participants simply had particularly good memory overall. Importantly, it also lends support to the theory that curiosity may be supported by both reward processes and networks of semantic knowledge.

Despite changes in reward processing, value still influences memory for older adults, and older adults are able to selectively encode high value information (Castel, Murayama, Friedman, McGillivray, & Link, 2013; Spaniol, Schain, & Bowen, 2014). Evidence suggests that the process of selectively encoding high value targets actually recruits semantic brain regions in order to facilitate deeper levels of encoding, and that the degree to which this occurs predicts subsequent memory for high value targets in both younger and older adults (Cohen, Rissman, Suthana, Castel, & Knowlton, 2014; Cohen et al., 2016). The interaction between these two networks in these studies shows how they may promote memory in the case of curiosity.

Across multiple domains, older adults have been shown to use semantic knowledge to compensate for deficits in episodic memory (Umanath & Marsh, 2014a). Mirroring the results of our two memory tests, older adults have been shown to perform just as well as younger adults on memory tests when the content to be remembered links with existing knowledge or schemas, whereas they perform much worse when they must rely solely on episodic memory (McGillivray & Castel, 2017). Semantic knowledge networks have been shown to promote memory as they develop across the lifespan (Brod, Werkle-Bergner, & Lee Shing, 2013), and the information gap model suggests they facilitate curiosity as well (Loewenstein, 1994; Wade & Kidd, 2019). As we age and acquire knowledge, the organization of these semantic networks may promote information seeking and curiosity, as well as successful encoding and later retrieval of the information that is gained.

However, fully understanding the overlapping roles of prior knowledge and reward processing will require a broader investigation of curiosity-related behaviors. We chose to use a trivia task, which necessarily requires one to access existing semantic knowledge. However, other measures of curiosity may provide different results. For example, several studies have linked patterns of eye movements during the free viewing of images to curiosity (K. R. Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1994; Gross et al., 2019; Risko et al., 2012). These behaviors are more exploratory, and less goal-directed, than pursuing answers to trivia questions. Willingness to wait is only one metric of curiosity, and future work should examine the roles that existing knowledge and reward seeking might play in a diverse set of information seeking behaviors.

In these studies, we used willingness to wait as a measure of curiosity. However, it's possible that factors beyond curiosity could influence waiting, and potentially explain the age differences we observed. People grow more patient with age, and older adults may wait not because of a high level of curiosity but because of a greater tolerance for waiting. In studies on temporal discounting, older adults do tend to show less discounting over time and more willingness to wait for future rewards (Eppinger et al., 2012; Green et al., 1994), however, this was not the case in our samples. Individual behavior on the temporal discounting tasks also did not predict waiting behavior on the curiosity task in either study, suggesting that patience does not explain the high curiosity in older adults. We also investigated the possibility that differences in time perception would make older adults more willing to wait, but we found no differences in tendencies to under or overestimate short time intervals between the two age groups. While neither of these measures explained curiosity behavior in our task, there may be other individual and generational differences involved. We used relatively small, cross-sectional samples in both studies, but it is certainly not representative of all older adults. Across ages, participants in this study were highly educated, with many holding advanced degrees. Further understanding of the role of curiosity in aging will require researchers to recruit larger, more representative, samples and follow them over time.

Although aging is often colloquially associated with declines in curiosity and exploration, the current studies demonstrated that this may not be the case. Future research into how and why curiosity changes across the lifespan will expand our understanding of the aging process and grant insight into ways to improve cognitive functioning and well-being throughout life. It will also shed light on the behavioral and neural mechanisms that drive curiosity, and enhance our understanding of curiosity's role in learning.

Supplemental Tables

Table S1.1: Whole brain contrast during question presentation for Wait > Skip

Region	Voxels	z-stat	X	Y	Z
Younger Adults					
L Middle Frontal Gyrus	1778	5.48	-28	12	52
R Cerebellum	1094	5.05	8	-92	-32
L Angular Gyrus	1034	4.61	-54	-56	20
L Middle Temporal Gyrus, temporooccipital	1022	5.05	-56	-50	-10
L Frontal Orbital Cortex	1000	5.57	-30	32	-18
R Thalamus	457	4.25	10	-8	20
L Frontal Medial Cortex	390	4.73	-2	40	-14
R Superior Temporal Gyrus, anterior	203	4.23	56	2	-18
L Postcentral Gyrus	193	4.21	-12	-44	54
L Precentral Gyrus	192	4.77	-42	-14	50
R Superior Frontal Gyrus	162	4.28	24	0	54
R Precentral Gyrus	110	4.33	42	-10	52
L Anterior Cingulate Gyrus	108	4.08	-2	4	28
L Precuneus Cortex	89	3.79	-8	-60	62
L Insular Cortex	89	4.87	-34	22	-2
Older Adults					
L Lateral Occipital Cortex, superior	402	5.05	-32	-78	32
L Middle Frontal Gyrus	273	4.61	-48	6	40
L Middle Frontal Gyrus	201	4.02	-36	2	64
L Frontal Pole	141	4.20	-44	46	8
R Superior Frontal Gyrus	95	4.17	22	6	54
Younger > Older					
R Cerebellum	255	4.55	26	-76	-34
L Lateral Occipital Cortex, superior	252	3.92	-56	-70	28
L Frontal Pole	205	3.70	-10	62	14
L Inferior Temporal Gyrus, anterior	186	3.76	-54	-8	-32
R Temporal Pole	111	3.60	42	24	-28
L Middle Frontal Gyrus	105	3.67	-40	30	46
L Frontal Pole	91	3.65	-22	46	32
R Angular Gyrus	87	3.22	52	-50	30

Coordinates in MNI Space. No clusters survived correction for contrasts of Older > Younger.

Table S1.2: Whole brain contrast during answer presentation for Remembered > Forgotten

Region	Voxels	z-stat	X	Y	Z
Younger Adults					
L Angular Gyrus	1380	5.30	-46	-56	26
L Frontal Pole/Superior Frontal Gyrus	1107	4.76	-16	44	50
R Cerebellum	985	5.71	42	-78	-42
L Middle Temporal Gyrus, temporooccipital	805	5.99	-66	-48	-8
L Frontal Pole	748	4.29	-44	44	-8
L Precuneus Cortex	536	5.23	-4	-56	24
L Interior Frontal Gyrus	483	4.61	-56	18	30
L Middle Temporal Gyrus, posterior	378	4.47	-68	-14	-24
R Middle Temporal Gyrus, temporooccipital	299	4.03	72	-42	-8
L Cerebellum	259	3.80	-38	-82	-42
L Frontal Pole	137	3.77	-2	58	-14
R Frontal Pole	127	3.91	38	36	-12
R Middle Frontal Gyrus	106	3.74	56	24	34
L Precentral Gyrus	100	4.00	0	-10	76
R Caudate	99	3.96	10	-2	16
L Cerebellum	92	4.11	-14	-86	-28
L Frontal Pole	85	3.86	-28	58	4
Older Adults					
R Middle Temporal Gyrus, anterior	862	4.88	64	-6	-22
R Intracalcarine Cortex	854	4.98	10	-80	16
L Middle Temporal Gyrus, anterior	582	4.33	-64	-2	-28
L Frontal Orbital Cortex	261	4.41	-48	26	-14
R Lingual Gyrus	230	4.60	16	-64	-12
L Frontal Pole	225	5.10	-2	56	-14
L Precuneus Cortex	214	4.50	-4	-62	10
L Lateral Occipital Cortex, superior	202	3.98	-38	-76	44
R Parahippocampal Gyrus, posterior	177	4.41	32	-30	-18
L Precuneus Cortex	162	3.87	-2	-56	26
L Temporal Pole	133	3.99	-46	14	-16
R Lateral Occipital Cortex, superior	98	3.85	54	-62	28
R Temporal Pole	91	3.83	36	24	-30
R Cerebellum	86	4.40	42	-70	-40
L Cerebellum	84	3.50	-36	-88	-24
Older > Younger					
R Occipital Fusiform Gyrus	531	3.96	34	-76	-16
R Intracalcarine Cortex	363	4.34	10	-80	16
L Lateral Occipital Cortex, inferior	119	3.56	-42	-74	8
L Occipital Pole	110	4.97	-30	-92	4
R Lateral Occipital Cortex, superior	94	3.75	32	-82	22
R Precuneus Cortex	92	3.77	16	-70	38
L Intracalcarine Cortex	82	3.87	-14	-84	6

Coordinates in MNI Space. No clusters survived correction for contrasts of Younger > Older.

Chapter 2: Translating curiosity into action: The development of epistemic curiosity and exploration in adolescence

In its most basic sense, curiosity can be understood as a desire to know (Berlyne, 1954), but just because we want to know something does not mean we know how to find out. One of the hallmarks of curiosity is its ability to drive us to pursue information. Recent work on curiosity has linked it to reward processing, where information has intrinsic value and can serve as a reward, just like money or food (Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016). What is not yet fully understood is how subjective feelings of curiosity are translated into goal-directed information seeking and subsequent learning.

Evaluating Curiosity through Behavior

People are very good at estimating their own levels of curiosity, and previous studies have used self-reports to ask questions about curiosity's role in learning. In studies using trivia questions, self-reports of curiosity predict subsequent memory for answers and correspond to increased activation in reward-related brain networks (Gruber et al., 2014; Kang et al., 2009; McGillivray et al., 2015). However, an evaluation of curiosity must not only assess subjective feelings of curiosity, but also examine specific exploratory behaviors that might result from it. Several studies have used willingness to wait as a way to measure goal-directed action. In these tasks, participants must choose whether to wait for an answer or skip to a new question, requiring a cost-benefit analysis of the value of the information compared to the amount of time required to attain it (Kang et al., 2009; Marvin & Shohamy, 2016). These studies demonstrate a link between curiosity and information seeking behavior, but represent only a narrow slice of the behavior that might be described as curiosity. In trivia paradigms, participants are pursuing a single piece of information that can relieve their curiosity, rather than exploring a broader information space.

While trivia questions represent epistemic curiosity, less directed and more exploratory behavior may also be a sign of curiosity. Visual stimuli may allow us to study this type of curiosity, as patterns of eye movements have been identified as a potential rich source of information about attention, decision making (Krajbich, Armel, & Rangel, 2010), memory (Hannula, 2010; Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011), and strategic information seeking (Yang, Lengyel, & Wolpert, 2016). In several studies, exploratory eye movements in free viewing tasks have been linked to trait measures of curiosity (Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1992; Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1994; Gross, Araujo, Zedelius, & Schooler, 2019). However, eye movements have not previously been used to measure intrinsically motivated exploratory behavior. Expanding the experimental focus of curiosity studies to include this type of exploration will provide rich data on the strategies we use to seek information when we are curious.

Development of Information Seeking

The majority of research on curiosity has focused on studies of adults, however studying it during development offers an exciting lens to gain insights into the candidate behavioral processes that drive curiosity. Recent studies have examined curiosity as a reward process, and the ways in which value information gets translated into action and learning has been studied extensively in children and adolescents. Adolescence is a period linked to high reward sensitivity, risk taking and impulsivity. On temporal discounting tasks, adolescents tend to show greater preferences for immediate rewards and a higher level of discounting compared to older participants (de Water et al., 2017; Scheres et al., 2006; Steinberg et al., 2009).

However, this heightened reactivity to rewards does not necessarily transfer to behaviors that maximize reward. While children and adolescents are adept at detecting sources of value, cognitive processes involving control and strategic planning are necessary to actually acquire them (Davidow, Insel, & Somerville, 2018). Reward-learning tasks require participants to learn about the environment in order to maximize rewards. These studies show a pattern of increased strategic thinking and information-seeking with age from childhood to adulthood (Decker, Otto, Daw, & Hartley, 2016; Gee et al., 2018; Somerville et al., 2017). While younger children do show heightened exploration in these tasks, it tends to be random, rather than strategic (Blanco & Sloutsky, 2019; Nussenbaum & Hartley, 2019). With age, adolescents get better at directed information seeking. They are better able to identify which pieces of unknown information will be most informative and maximize information gain and subsequent rewards (Nussenbaum et al., 2019). While these studies have only examined information seeking in the context of information that is useful for gaining other rewards, an important question is whether this will extend to non-instrumental information seeking and curiosity.

Curiosity in Adolescence

We can begin to understand how curiosity drives behavior by studying the development of curiosity in adolescence and early adulthood. Like adults, children and adolescents are good at assessing their own curiosity and assigning value to information. Trivia questions have been shown to successfully elicit curiosity and demonstrate related memory benefits in children as young as eight (Gruber & Fandakova, 2019; Walin et al., 2016), making them a good candidate to assess curiosity across ages. Using curiosity paradigms that require participants to seek out information, we can assess how the relationship between information value and information seeking changes with age. If only the assessment of subjective value of information matters, we might see higher curiosity in adolescents than adults, corresponding to high adolescent reward sensitivity. However, if the process of translating value to information seeking mirrors the development of other strategic goal-directed behavior, we may see an increase in curiosity with age as participants learn to translate information value into action.

In the current study, we sought to measure age related changes in curiosity during the period from late childhood into adulthood. We used two complementary tasks that required participants to seek information (Figure 1), one examining epistemic curiosity using trivia questions, and a second novel exploration task to measure information-seeking and uncertainty resolution using occluded visual stimuli. In a sample of 70 participants ranging from 10 to 30, we asked three questions. 1) how does epistemic curiosity and related memory change with age during this period? 2) How does exploratory information-seeking change with age during this period? and 3) What is the relationship between these two types of behavior and does it change with age? Along with the two main curiosity tasks, we included measures of self-reported curiosity, memory, temporal discounting, semantic knowledge, executive control and impulsivity.

Method

Participants

We recruited participants between the ages of 10 and 30, to be able examine the effect of age continuously from adolescence into adulthood (N = 70, Median = 18, Mean = 17.26, N Female = 37). Participants were recruited from Columbia University and the surrounding community using flyers. They were paid $35 for the 2 hour study, or, in the case of adult participants recruited from undergraduate psychology courses, received course credit. Participants who were under 18 provided informed assent, and informed consent was also provided by a parent or guardian. Adult participants provided informed consent. Consent procedures were approved by the Columbia University IRB. No participants were excluded from analysis, although in a few cases participants missed completing individual tasks due to time constraints or technical problems. In these cases, participants were excluded from the analysis of that task, unless indicated below. Tasks missing data were the delay discounting task (3 missing), memory task (3 missing), and the visual exploration task (2 missing). No subjects were missing data from the two trivia tasks.

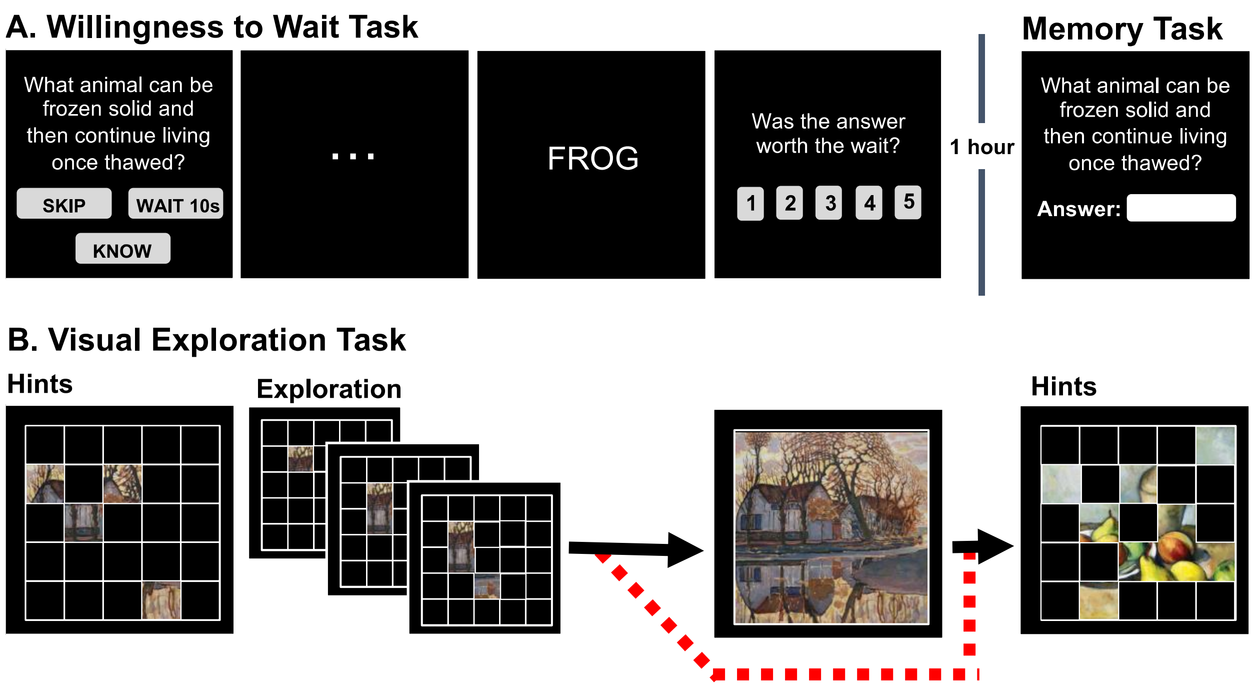

Figure 2.1: In the willingness to wait task, **(A)** participants see trivia questions and choose whether to wait for the answer or skip to the next question. Choosing know also skips to the next question. Once the answer is revealed, participants rate whether it was worth waiting for. The task continues for 15 minutes, no matter how much participants choose to skip. After an hour, participants are presented with a surprise memory test for the answers they waited for, and the answers they said they knew. In the visual exploration task **(B),** each trial starts with a hint phase, where the painting is shown with 0-10 squares briefly uncovered. All squares are re-covered for the exploration phase, and participants can reveal them by focusing their gaze on a square. After revealing three squares, they are given the option keep exploring or skip to the next paining at any time. Once the time limit has elapsed (60 seconds) or they have chosen to skip, the next hint phase begins.

General Analysis Approach

All analyses were conducted using Bayesian modeling techniques. For each task we constructed multilevel linear and logistic regression models using the brms package in R (Bürkner, 2017) to predict trial-by-trial data. These models included random intercepts for participants and stimuli, and random slopes where appropriate. All models used minimally informative priors as recommended by Gelman (2008). Predictors were centered and scaled, and priors were set with Cauchy distributions with mean zero and standard deviations of 10 for intercepts and 2.5 for predictors. For comparisons between tasks, we calculated overall scores for each task, and computed correlations using the Bayesian correlation test from the Psycho package in R (Makowski, 2018).

Curiosity Tasks

Willingness to Wait

We used a task that tests willingness to wait for information as a measure of curiosity (Kang et al., 2009; Marvin & Shohamy, 2016). In this task, participants read a series of trivia questions and chose between three options (**Figure 2.1A**). If they wanted to know the answer, they had to wait a certain number of seconds (Wait). Wait times varied between 5 and 20 seconds, and the specific wait time for each trial was explicitly shown on the screen. If participants chose to wait, the answer appeared after the designated wait time, and then they were asked if the answer was "worth the wait", rated on a scale of 1 (not at all) to 5 (extremely). Alternatively, they could skip ahead to the next question immediately without getting the answer (Skip). If they already knew the answer, they could choose Know, and this would also move them to the next question immediately. Participants could wait or skip for as many questions as they wanted. The task lasted for 15 minutes, and participants were told that skipping questions would not make it end early.

To analyze this task, we used multilevel logistic regression to predict whether participants would skip or wait (know trials removed). Predictors included age, wait time, and a standardized measure of question curiosity level (see below), as well as trial number. Random effects were included for each participant and each question.

Questions were selected from a larger database of questions previously rated by a separate group of participants on MTurk (N=800, ages ranging from 18-75). Online participants rated their curiosity about the trivia questions on a nine point Likert scale from “Not at all curious” to “Extremely curious.” Each question was rated by between 30 and 60 people. Ratings were then averaged for each question and z-transformed, providing a standard measure of how curious people tended to be about each question. Questions in the database were categorized based on content, and we specifically chose questions from the history, science, geography and general knowledge questions, and excluded pop culture and sports questions, which tend to be more specific to a particular era and therefore could be less relevant across different age groups. We also excluded any other questions for which there was a large difference in the probability of knowing the answer based on age (e.g. pop culture and sports questions). We ended up with a list of 200 questions, from which we drew randomly for each trial.

Trivia Rating Task

To assess self-reported levels of epistemic curiosity, participants completed a separate task with a new series of trivia questions pulled from the same pool as the previous task. For each question, they explicitly rated their curiosity on a sliding scale from “Not at all curious” to “Extremely Curious”. Participants used the mouse to slide an indicator left or right on the scale.

The scale had no numeric values, but the center was marked with a vertical line. This was followed by a question about their confidence in knowing the answer using the same type of scale. The answer was then presented, followed by another rating scale asking whether this was a satisfying answer to the question, again using the continuous scale. This task lasted until participants had rated 25 questions which they did not already know (defined as questions they rated below 95% confidence). The mean number of trials was 28.04, and most participants did between 25 and 40 trials. However, there was one who completed 59 trials. Analysis focused on how age and question curiosity predicted each of the three ratings in a series of multilevel linear regressions, with random effects for each participant and each question.

Trivia Memory Task

In order to test the effect of curiosity on memory, participants were given a surprise memory test for the answers to the trivia questions they saw in both the Ratings task and the Willingness to Wait task. Questions which participants claimed they knew were also included in the test. Questions were presented one at a time, and participants typed their answers into a field below. The test was untimed and participants were encouraged to guess if they weren't sure. This task always occurred last to ensure a consistent amount of time between learning (always the first two tasks) and test.

Visual Exploration Task

While curiosity is often measured with trivia tasks, it is important to also assess how curiosity is reflected in other behaviors that are not specific to semantic knowledge. To this end, we developed a visual exploration task, in which participants explore hidden images using gaze-contingent eye tracking (**Figure 2.1B**). On each trial, an image was obscured by a grid of 25 black squares. Each trial was divided into two parts, the hint phase and the exploration phase. In the hint phase, some boxes would disappear for a period of two seconds, giving a “hint” regarding the image below. At the end of the two seconds, all the black squares would reappear, and the participants would begin exploring. The placements of the hints were random. The number of hints was drawn from a uniform distribution between 0 and 10. Once the exploration phase began, focusing eye gaze on the center of a square for 500 milliseconds caused a square to disappear, revealing the image beneath. There was a total of 24 trials, each lasting a maximum of 60 seconds. Participants could choose to explore the image for the entire time, or they could move to the next trial at any after they revealed at least three squares. The 60 second limit was more than enough time to reveal the entire image. The images used were paintings done by famous artists. There were also three trials were blank, with only a white background appearing when the black squares were removed. The order of the trials was randomized for each participant.

Eye movements were recorded using an Eyelink 1000 Plus infrared eye tracker (SR-Research, Ottawa, Ontario, Canada) at 500Hz. Participants’ heads were stabilized using a chin and forehead rest. Continuously reported x-y coordinates of eye position provided by the eye tracker were used by Matlab to determine which regions of the screen were being viewed, and if the time spent looking at a specific box exceeded 500ms, that box would be uncovered.
The analysis of this task focused on how many boxes were revealed in each trial.

We used multilevel logistic regression to test whether age predicted the number of squares revealed on each trial (out of 25). Number of hints, trial type (art or blank), and trial number were also included as predictors. Random effects were included for each painting and each participant.

Between-Task Analysis

In order to assess the relationship between exploration and epistemic curiosity, we computed correlations between participants' average scores on the waiting task (proportion of trials waited), exploration task (average boxes revealed) and trivia rating task (average curiosity rating).

Additional Tasks

Temporal Discounting

As the willingness to wait task requires participants to trade time for information, we wanted to test whether individual differences in general willingness to wait for rewards predicted behavior on that task. Participants completed a delay discounting task requiring them to make hypothetical choices between one amount of money today or a larger amount in the future. The monetary value today was randomly drawn for each trial from a normal distribution with a mean of 20 dollars and a standard deviation of 5. The later amount was then calculated as either 5%, 10%, 15%, 25%, 35% or 50% larger than the today amount, at time delays of 1, 2, 3, 4, 5, or 6 weeks. The trial types were counterbalanced so that all reward ratios occurred for all delay lengths, resulting in 36 total trials.

Traditional analysis of discounting data involves calculating a value, k, for each person which quantifies their tendency to discount, combining the contributions of both delay and reward into a single number. However, recent work on discounting tasks has suggested that logistic regression can be used to derive individual estimates for the effect of both time delay and reward size on discounting choices (Wileyto et al., 2004; Young, 2018). A multilevel logistic regression was used to predict now/later choices using both delay time and reward ratio as predictors. Random slopes and intercepts are included for each participant, and examination of the participant-level coefficients provides individual estimates for the degree of influence each factor had on individual choices. For example, one participant may rely heavily on reward value to make decisions, and ignore the delay, while another might do the opposite (Young, 2018). These individual coefficients were then used as predictors in the models for the Skip/Wait task. We also analyzed the task data on its own to assess age related differences in delay choices.

Cognitive Measures

We expected there to be age-related differences in levels of impulsivity, general knowledge and executive control, so to assess the effects of these measures on curiosity participants completed three assessments that are part of the NIH toolbox cognitive battery (Weintraub et al., 2013). This included the Picture Vocabulary Test, a measure of vocabulary and general semantic knowledge, as well as two measures of inhibitory control and executive function, the Flanker Inhibitory Control and Attention Test and the Dimensional Change Card Sort Task, which we thought might be related to cognitive control and goal-directed behavior. For a small number of participants these measures were omitted because of time constraints. In these cases (N=5 for Dimensional Card Sort Task and Flanker Task, N=4 for Picture Vocabulary Test), values were imputed based on other demographic variables using multiple imputation measures via the mice package in R (van Buuren & Groothuis-Oudshoorn, 2011). Imputing these values allowed us to include all participants in the analysis and to test whether models that included these variables explained more variance in the data than models that did not. For all three measures, NIH Toolbox computes both age corrected and age uncorrected scores. Since we were interested in changes across ages, we used the uncorrected scores for all analyses.

Questionnaires

We also had participants complete a series of questionnaires. Questionnaires included two trait curiosity measures: the Curiosity and Exploration Inventory (CEI-II: Kashdan & Steger,

2007) and the Interest and Deprivation Curiosity Scales (Litman, 2008). Participants who were under 18 additionally completed a developmental questionnaire (Petersen, Crockett, Richards, & Boxer, 1988), and their parents completed demographic information on education levels and income, and the Child Behavior Checklist (Achenbach, 1991).

Results

Willingness to wait

The willingness to wait task showed evidence for age-related increases in curiosity. The probability of choosing to wait for an answer, rather than skipping, increased with age (b = 0.43, 95% CI [0.12, 0.75]; **Fig. 2.2A**). While, the question curiosity score also increased the probability of waiting (b = 0.66, 95% CI [0.50, 0.81]), the positive effect of age on waiting was present across all levels of question curiosity, as shown in **Fig. 2.2B**, (b = -0.04, 95% CI [-0.19, 0.12]). Additionally, while longer wait times decreased the probability of waiting (b = -0.53, 95% CI [-0.66, -0.40]), older participants were more willing to wait across all wait lengths (b = 0.02, 95% CI [-0.11, 0.15]).

To test whether the effect of age was consistent across questions or driven by a subset of questions that were particularly appealing to adults, we examined the random slopes coefficients for the effect of age on each question. This showed that out of the two hundred questions, 190 had a predicted positive slope for age. To test whether or not increases in general knowledge and executive functioning explained the relationship between age and curiosity, we created a second model with individual scores on the three NIH measures as covariates. For all three measures, the credible intervals included zero (PVT: b = 0.30, 95% CI [-0.07, 0.66]; DCCS: b = 0.01, 95%

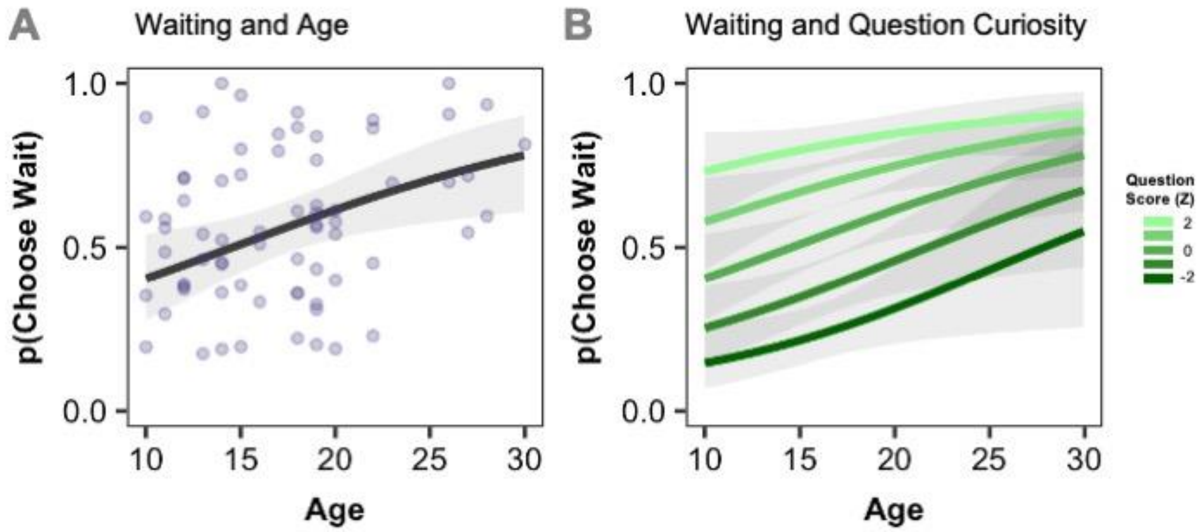

Figure 2.2: In the waiting task, **(A)** older participants were more likely to wait for answers to trivia questions than younger participants. This was true across levels of question curiosity **(B)**. Older participants were more willing to wait for both high and low curiosity questions.

CI [-0.37, 0.38], Flanker: *b* = -0.33, 95% CI [-0.68, 0.02]). Including this term in the model decreased the estimate for the effect of age compared to the first model, and the new credible interval slightly overlapped zero (*b* = 0.36, 95% CI [-0.01, 0.73]). This suggests that some, but not all, of the age effect may be explained by increases in executive functioning and general knowledge. However, adding the additional covariates did not improve the model fit based on WAIC (model 1: *WAIC* = 3021.12, *SE* = 51.53, model 3: *WAIC* = 3021.74, *SE* = 51.81).

This waiting requires participants to trade time for information, and we wanted to test if behavior was predicted by a participant's general willingness to wait on the monetary discounting task. We created another version of the model with the two individual difference measures derived from the temporal discounting task entered as predictors. Neither sensitivity to reward (*b* = -0.04, 95% CI [-0.39, 0.32]) nor sensitivity to delay (*b* = 0.22, 95% CI [-0.14, 0.59]) predicted willingness to wait for answers, and including them in the model did not improve the model fit based on a comparison of WAIC values (model 1: *WAIC* = 3021.12, *SE* = 51.53, model 2: *WAIC* = 3021.80, *SE* = 51.64).

Curiosity Rating Task

In the rating task, we looked for age-related changes in self-reported curiosity, confidence and satisfaction ratings based on age and question curiosity. Curiosity ratings showed a modest increase with age, although the credible interval of the effect bordered zero (*b* = 0.11, 95% CI [-0.001, 0.22], **Fig. 2.3**). As in the waiting task, there was a large effect of question curiosity, where questions with higher average curiosity scores tended to be rated higher by the individual participants (*b* = 0.25, 95% CI [0.18, 0.31]), but the effect of age was consistent across levels of question curiosity.

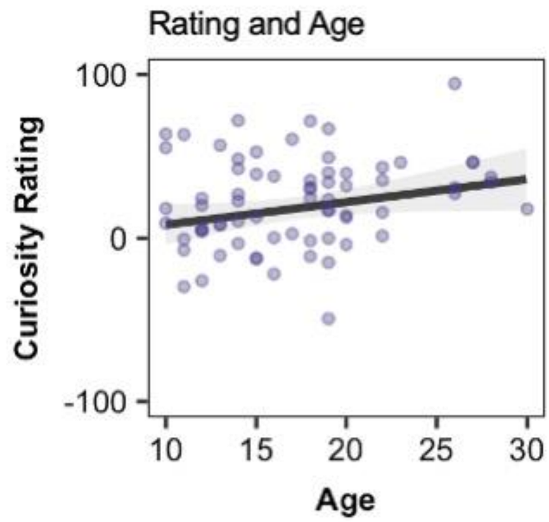

Figure 2.3: In the rating task, older participants gave higher curiosity ratings than younger ones. Line shows model prediction with 95% CI. Dots show average curiosity ratings by participant.

We next analyzed the confidence and satisfaction ratings, both for their own sake and to test whether the relationship between age and curiosity was specific to curiosity or due to a general tendency of older participants to make higher ratings. Age did not predict confidence (*b* = 0.04, 95% CI [-0.06, 0.14]). There was a small potential effect of question curiosity on confidence, but the 95% credible interval overlapped zero (*b* = 0.08, 95% CI [-0.003, 0.16]). There was no interaction between age and question curiosity (*b* = -0.005, 95% CI [-0.05, 0.04]). The pattern of results was similar for answer satisfaction ratings. There was no effect of age (*b* = 0.11, 95% CI [-0.03, 0.24]), though there was a positive effect of question curiosity where the answers to higher curiosity questions were seen as more satisfying (*b* = 0.14, 95% CI [0.08, 0.20]), with no interaction between age and question curiosity (*b* = 0.01, 95% CI [-0.04, 0.06]).

Relationship between individual ratings and standardized ratings: As the standardized question curiosity scores were derived from a sample of adults, we wanted to investigate whether these ratings were a good reflection of question curiosity for our younger participants. We split our sample based on those under 18 (N=35), and those over 18 (N=35), and calculated average ratings per question for each group. We then correlated these ratings with the online sample. For the older age group, the correlation between ratings was 0.34 (95% CI 0.21-0.47), and for younger participants it was 0.43 (95% CI 0.3-0.56). This suggests that the younger participants may be making lower ratings in the task, but high curiosity questions are still high, and low curiosity questions are low.

Memory for Trivia

The memory task included questions from both the willingness to wait task and the rating task. Initial analyses suggested there were no differences in memory scores between the two tasks so they were combined into one analysis. The probability of remembering increased with age (*b* = 0.71, 95% CI [0.37, 1.05**]; Fig. 2.4A**), and standardized question curiosity (*b* = 0.73, 95% CI [0.44, 1.02]), with no interaction (*b* = -0.06, 95% CI [-0.19, 0.08]; **Fig 2.4B**). There was no difference in memory performance between the two tasks (*b* = 0.10, 95% CI [-0.14, 0.33]), and the effects of age (*b* = 0.06, 95% CI [-0.17, 0.29]) and question curiosity (*b* = -0.16, 95% CI [-0.41, 0.09]) did not differ between them. The total number of items to remember did not affect memory (*b* = 0.02, 95% CI [-0.30, 0.34]).

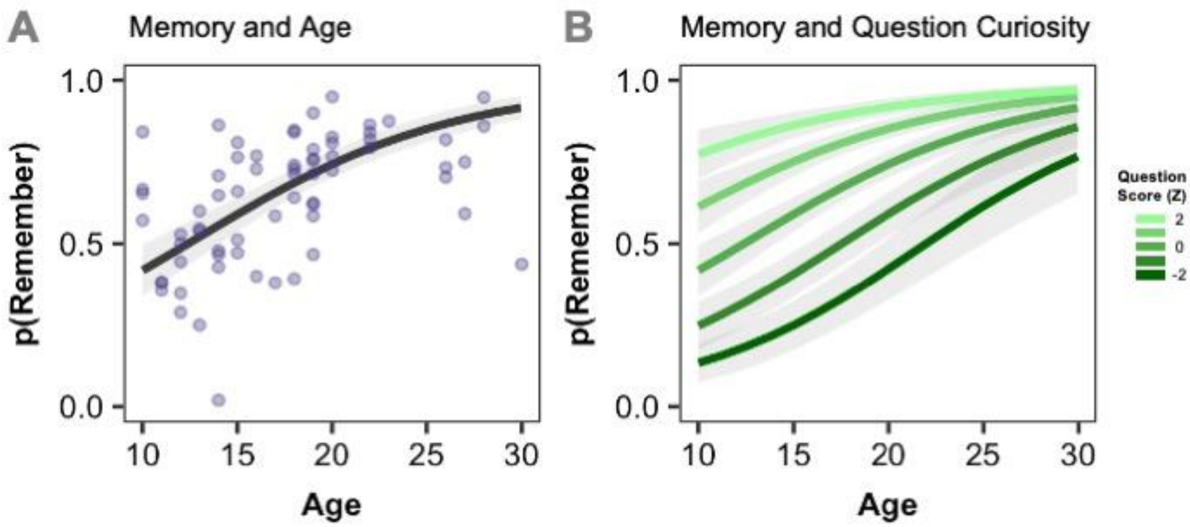

Figure 2.4: In the memory task, **(A)** older participants were more likely to remember answers than younger participants, regardless of task. This was true across levels of question curiosity **(B)**. Although younger participants were still sensitive to question curiosity, older participants were more likely to remember answers for both high and low curiosity questions. Lines represent model predictions with 95% CIs, dots show memory scores (proportion of answers remembered) for each participant, with both tasks combined.

To test whether the effect of age on memory was due to a more general increase in intelligence and executive functioning, we created a second model with the three scores from the NIH toolbox (picture vocabulary test, flanker task, and card sorting task) as covariates. Results showed a large positive effect of vocabulary scores on memory where individuals with higher vocabulary scores were more likely to remember answers (*b* = 0.97, 95% CI [0.70, 1.26]). The other two tasks did not predict memory (Flanker: *b* = -0.05, 95% CI [-0.33, 0.23]; Card Sorting: *b* = -0.002, 95% CI [-0.28, 0.29]). Compared to the first model, the predicted effect of age on memory was smaller but still positive (*b* = 0.29, 95% CI [0.007, 0.57]). The effect of question curiosity on memory was consistent with the first model (*b* = 0.72, 95% CI [0.44, 1.02]). Adding the additional predictors did not improve model fit based on WAIC (model 1: *WAIC* = 2903.47, *SE* = 64.42, model 2: *WAIC* = 2898.76, *SE* = 64.66).

Visual Exploration Task

In the visual exploration task, older participants explored more per trial than younger participants, measured by the number of boxes that they uncovered for each painting (*b* = 1.50, 95% CI [0.20, 2.86]). As expected, the number of boxes uncovered was higher for trials where there was a painting compared to trials where the squares covered only a white background (*b* = -3.93, 95% CI [-5.98, -1.81]). However, there was an interaction between age and trial type, such that all participants explored the same amount in the white trials, and the effect of age was seen only in the painting trials (*b* = -1.80, 95% CI [-3.49, -0.14]; **Fig. 2.5**). For all ages, there was a negative main effect of the number of hints given, where participants explored less if they'd been given more hints (*b* = -0.50, 95% CI [-0.88, -0.13]), and also a negative effect of trial number, where exploration decreased as the task progressed (*b* = -0.49, 95% CI [-0.77, -0.21]).

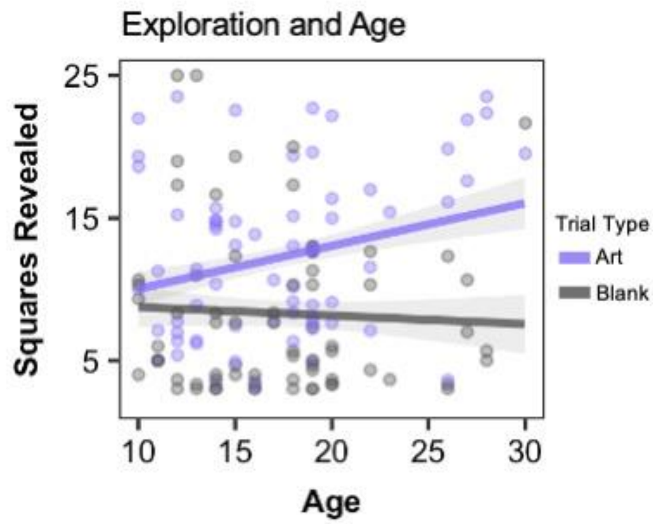

Figure 2.5: In the exploration task, older participants revealed more of the hidden images than younger participants (purple). In trials where there was no image (grey), there was no effect of age. Lines show model estimates with 95% CIs. Dots show averages for each participant on each type of trial.

Correlations between Curiosity Measures

We found positive relationships between all three measures of curiosity. Participants who waited for a higher proportion of questions on the waiting task also tended to reveal more in the exploration task. (*r* = 0.35, 95% CI [0.12, 0.56], **Fig. 2.6A**). They also had higher average ratings of curiosity (r = 0.36, 95% CI [0.13, 0.56]; **Fig. 2.6B**). Finally, average exploration and average curiosity ratings were also positively correlated (r = 0.46, 95% CI [0.24, 0.64]; **Fig. 2.6C**).

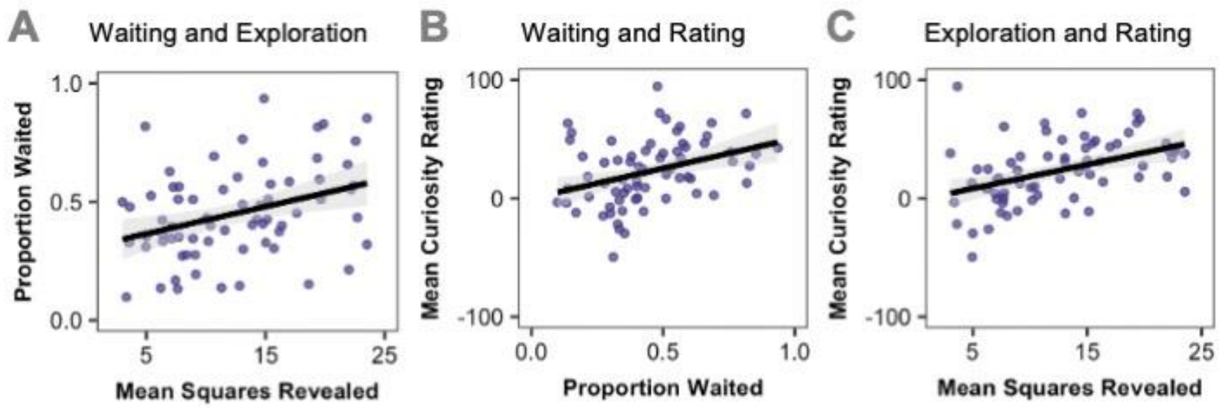

Figure 2.6: Average scores were correlated across all three behavioral curiosity measures. The proportion of trials waited on the waiting task was positively correlated with the average squares revealed across trials in the exploration task **(A)** and with the average curiosity rating on the rating task **(C).** The average ratings and average squares revealed were also positively correlated **(B).** Lines show model estimates with 95% CI, dots show individual subjects scores, colored by age.

Delay Discounting Task

While individual discounting parameters were added to models for other tasks as subject-level covariates, we also constructed a model for the discounting data to measure the effect of age on choices to wait for the later, larger amount of money. The multilevel logistic model included age as well as the base value of the trial (the immediate option), the ratio between the later amount and immediate amount, and the length of the delay, as well as their interactions with age. The probability of choosing the later option increased with the value of the trial (b = 0.54, 95% CI [0.39, 0.71]), increased with the reward ratio (b = 2.15, 95% CI [1.83, 2.52]), and decreased with the time delay (b = -1.46, 95% CI [-1.77, -1.19]). There was no main effect of age on the probability of choosing the later option (b = 0.17, 95% CI [-0.56, 0.91]), and no interactions between age and trial value (b = 0.06, 95% CI [-0.10, 0.23]) or delay time (b = -

0.05, 95% CI [-0.32, 0.24]). There was a potential interaction between age and reward ratio, where the slope of the effect of age was positive for trials with high reward ratios, but flat for trials with low reward ratios (b = 0.32, 95% CI [-0.004, 0.65]).

Discussion

In this study, we sought to measure curiosity and exploratory behavior across adolescence and into adulthood. Using multiple behavioral measures of curiosity, we found evidence for higher levels of curiosity in older participants compared to younger ones in a sample ranging from 10 to 30 years old. Older participants were more willing to wait for answers to trivia questions and showed more exploratory behavior in a visual exploration task. Additionally, older participants had higher explicit curiosity ratings for trivia questions. When their memory for answers was tested, participants of all ages showed positive effects of curiosity, where high curiosity answers were remembered better, but older participants had much better memory performance, on average, than younger ones. Across the three curiosity tasks, behavior was correlated such that participants who showed high curiosity on one task also showed high curiosity on the others.

This pattern of results is not consistent with the prediction that curiosity is purely a form of reward-seeking. While prior work has suggested that sensitivity to rewards is high in adolescence and declines into adulthood, in the present study, we observed an increase in curiosity with age. The age-related increase in curiosity may be related to changes in goal-directed behavior during childhood and adolescence. Reward-learning studies have shown a shift from random to targeted exploration during adolescence (Blanco & Sloutsky, 2019; E. Schulz, Wu, Ruggeri, & Meder, 2019; Somerville et al., 2017; Sumner et al., 2019). Older adolescents and adults are better at identifying and exploring options that have the highest probability of being informative, rather than exploring randomly (Nussenbaum et al., 2019). Younger participants may feel curious, but lack the fully developed cognitive systems for control and strategy that allow them to translate this into action.

However, changes in curiosity in this study cannot be completely explained by differences in control, impulsivity or patience. We did not observe a link between curiosity and discounting behavior on the delay discounting task. Willingness to wait for larger monetary rewards did not predict willingness to wait for answers. One possibility however is that the discounting task was not a good index of reward-driven behavior, because decisions were hypothetical, so results may have been different if real money had been at stake. Indeed, the results of our discounting task did not show age effects that had been described in previous studies, in which older participants are more willing to choose the later reward (de Water et al., 2017; Scheres et al., 2006; Steinberg et al., 2009). Nonetheless, this pattern of results suggests that the relationship between reward and curiosity may be more complex than has previously been suggested.

Another factor that may be driving the increase in curiosity with age is that general semantic knowledge also accumulates with age. Semantic knowledge has previously been identified as an important contributor to epistemic curiosity, as feelings of curiosity can arise when we detect gaps in knowledge, and having more knowledge allows for better detection of these gaps (Loewenstein, 1994; Wade & Kidd, 2019). This may also explain how information gets assigned value – information that can resolve uncertainty and fill a gap in our understanding is highly desirable, while information on a topic we know nothing about may not be as appealing. In our sample, age was positively associated with vocabulary, which has been used as a measure of general semantic knowledge and crystalized intelligence (Weintraub et al., 2013).

However, we did not find strong evidence that it predicted curiosity. Future research should more thoroughly examine the role of semantic knowledge in curiosity, especially its role in exploratory behaviors that do not explicitly require it. While it is easy to see the value of existing knowledge for the trivia task, it may have a different role in exploration tasks like ours where prior knowledge of the stimuli is not expected.

While its connection to feelings of curiosity is not completely clear, age related increases in semantic knowledge may explain the beneficial effect of curiosity on memory. Prior knowledge has been shown to facilitate memory by providing a framework into which incoming information can be integrated. As we get older, our knowledge base grows and this structure also facilitates reactivation of memories (Bjorklund, 1987; Brod, Werkle-Bergner, & Shing, 2013; Shing & Brod, 2016). In the memory test, vocabulary scores did strongly predict successful recall. It is possible that a network of semantic knowledge that is continually expanding with age and experience facilitates both curiosity and memory for information.

One alternate explanation for the age-related increase in curiosity could be that the adolescents in our sample were simply less curious about the kinds of questions that were used as stimuli. However, our experimental design and control analyses build confidence that this explanation does not likely account for our developmental findings. When selecting stimuli, we tried to counteract this by excluding questions from the database that showed a strong relationship between age and already knowing the answer. However, the online raters were all over 18, so it's possible that their ratings do not match the ratings of younger participants. When we split our sample into participants older and younger than 18, the younger participants showed an equally strong correlation with the standardized ratings as the older participants. This shows that their perceptions of the interestingness of the questions did not fundamentally differ from the adults, as they tended to rate the high curiosity questions as high and low curiosity questions as low. Finally, we saw age effects in the exploration task as well as the trivia tasks, which did not require existing knowledge in the same way as do trivia questions. Taken together, this suggests that the age effect cannot simply be explained by a lack of interest in the particular stimuli we chose on the part of the younger participants.

Curiosity is a powerful tool for learning. A better understanding of how curiosity drives behavior would not only help our understanding of the mechanisms underlying different forms of curiosity, but would provide direction for educational interventions that harness curiosity to improve learning across the lifespan.

Chapter 3: Characterizing curiosity across traits, states and behaviors

Curiosity is a universal human experience. At some point or another, we have all felt the drive to pursue information. However, a commonly cited challenge in the scientific study of curiosity is the lack of a concise idea of exactly what curiosity is, and how it should be measured (Grossnickle, 2016; Kidd & Hayden, 2015). Across studies of curiosity, two broad approaches have emerged. The first, grounded in personality psychology, treats curiosity as a stable personality trait and asks questions about how it tracks with other person-level attributes. A second approach has developed more recently, which takes a neurobiological perspective and emphasizes behavior -- treating curiosity as a transient state which drives information-seeking within specific tasks. While both these approaches fall under the umbrella of curiosity, we lack a firm understanding of exactly how traits and states of curiosity relate to one another. In this study, we aimed to test the extent to which person-level traits related to curiosity predicted information-seeking on a state level, using a framework developed by Gillan, Kosinski, Whelan, Phelps, & Daw (2016) for relating behavior to multidimensional subject-level constructs.

Trait curiosity is a person's general tendency to experience curiosity across many situations, and is typically measured by self-report. A variety of different scales have been developed over the last four decades (e.g. Collins, Litman, & Spielberger, 2004; Kashdan et al., 2009a; Litman, 2008; Naylor, 1981; Spielberger, Jacobs, Crane, & Russell, 1979), most focused on a specific sub-type of curiosity, including epistemic, perceptual, social and deprivation-based. Studies of trait curiosity have shown that it can predict educational achievement (Alberti & Witryol, 1994; Craig, 2009; Shah, Weeks, Richards, & Kaciroti, 2018; van Schijndel, Jansen, & Raijmakers, 2018b; von Stumm, Hell, & Chamorro-Premuzic, 2011), well-being (Jovanovic &

Brdaric, 2012; Jovanović & Gavrilov-Jerković, 2014), life satisfaction (Kashdan & Steger, 2007; Kawamoto, Ura, & Hiraki, 2017), and even decreased mortality (Swan & Carmelli, 1996). However, these measures cannot speak to the cognitive and behavioral mechanisms that drive curiosity in the moment, and that link curiosity and memory.

The other approach to studying curiosity focuses on information-seeking behavior on specific tasks in response to specific stimuli. This can be thought of as state-level curiosity, and tasks tend to use either active, explicit ratings of curiosity or operationalizations of curiosity in behavior (e.g. waiting or exerting effort). Stimuli include trivia questions (Gruber et al., 2014; Kang et al., 2009; Ligneul, Mermillod, & Morisseau, 2018; Litman, Hutchins, & Russon, 2005; Marvin & Shohamy, 2016), blurry images (Jepma, Verdonschot, van Steenbergen, Rombouts, & Nieuwenhuis, 2012) and unknown gambling outcomes (Charpentier et al., 2018; Kobayashi & Hsu, 2019b; Kobayashi, Ravaioli, Baranès, Woodford, & Gottlieb, 2019; van Lieshout et al., 2018). Behavioral tasks can investigate how and when curiosity is elicited, how it drives behavior and memory, and ask questions about the neural processes that contribute to curiosity. These tasks have hinted at links between curiosity and more generalized reward systems, where information can been seen as a reward, even when it is non-instrumental and non-strategic (Gruber et al., 2014; Kang et al., 2009; Kidd & Hayden, 2015; Marvin & Shohamy, 2016).

While it may seem intuitive that individuals high in trait curiosity will be more curious in specific situations, the link between trait and state curiosity remains poorly understood. Some studies have found links between trait curiosity and exploratory behavior, such as pursuing answers to trivia questions (Litman et al., 2005) and exploratory eye movements (Baranes, Oudeyer, & Gottlieb, 2015; Gross et al., 2019; Hoppe et al., 2015; Risko et al., 2012). However, most research has focused only on one measure of curiosity, without considering others.

Reconciling the disparate threads of curiosity research is challenging, but a recent study provides a method for investigating these questions (Gillan et al., 2016). They compared performance on a behavioral task of model-based learning to individual differences on trait level goal-directed control and compulsive behavior, using an array of self-report measures of psychiatric symptomology. This allowed them to extract latent constructs related to individual differences, and test which of these predicted behavior.

Understanding the link between trait and state curiosity may help to resolve open questions in the field. For example, it has been proposed that curiosity should decline across the lifespan, mirroring other changes in the reward processing (Sakaki et al., 2018). However, experimental evidence on this topic has produced mixed results. While some studies have shown decreasing trait curiosity with age (Robinson et al., 2017), others have not (Giambra et al., 1992; Stoner & Spencer, 1986). Behavioral measures of state curiosity have shown stable levels, and even increases, in curiosity across old age (K. R. Daffner et al., 1994; Galli et al., 2018b; McGillivray & Castel, 2017) A better understanding of curiosity may result from a more thorough characterization of the relationship between behavioral measures of curiosity, trait measures of curiosity and individual differences like age.

In the current study, we sought to examine the relationship between behavior on a curiosity task, trait measures of curiosity, and related constructs using a large online cohort with ages ranging from 20 to 73, following the analysis strategy of Gillan et al. (2016). We selected a validated behavioral measure of curiosity, the willingness-to-wait task (Kang et al., 2009; Marvin & Shohamy, 2016), in which participants must choose to wait a specified length of time in order to receive the answer to a trivia question. With this task, we aimed to replicate previous findings that the perceived subjective value of each answer would predict both willingness to wait and subsequent memory. We also chose a series of trait scales that evaluate different types of curiosity, along with related measures, including impulsivity, openness to experience, need for cognition, and need for closure. We tested how these different personality traits related to one another by performing a factor analysis to extract a latent structure underlying the overlapping set of trait constructs. We then tested the relationship between trait measures and behavior on the waiting task, both individually and as combined factor scores. We predicted that individuals with trait scores indicating higher curiosity would be more willing to wait for answers on the trivia task. Finally, we turned our attention to the question of aging, to test whether trait and state curiosity measures show similar trajectories across the lifespan.

Method

Participants

745 participants were recruited via Amazon Mechanical Turk (MTurk). Of these, 662 were included in the final analysis (see Exclusion Criteria below). The final sample was 41.8% female. The mean age was 37.37, (sd = 11.35) with ages ranging from 20 to 73. All participants were required to be from the US and to have previously completed 100 successful MTurk tasks (HITs). All participants provided informed consent using an online form at the start of the task. The Columbia University IRB approved all procedures.

Exclusion Criteria

Exclusion criteria were applied sequentially. Starting with the original 745 participants who completed the consent process, 25 were excluded for completing fewer than half of the measures. In all cases, the missing measures were questionnaires, since the curiosity tasks were always completed first. An additional 10 participants were excluded for failing to register a response for more than 20% of the trials of the waiting task. The next criterion was to exclude participants whose average reaction time on the waiting task was less than two standard deviations below the overall mean reaction time, but no participants fell below this threshold. Finally, two of the questionnaires included catch items to test for attention (e.g. if you are reading this question, select "slightly agree" for this question). 48 participants were excluded for failing to answer catch items correctly. This resulted in a final sample of 662, although since some participants were still missing questionnaires, individual analyses have different subject totals. The number of participants for each analysis are reported with the results.

Missing data imputation

Within each questionnaire, some participants had missing data for individual items. In these cases, which represented less than one percent of the data for each scale, we used multiple imputation methods to impute those values based on the other items in that subscale. Imputation was not performed if participants were missing more than 50% of items on the subscale. Imputation was implemented using mice package in R (van Buuren & Groothuis-Oudshoorn, 2011). Twenty imputed datasets were calculated for each subscale of each questionnaire for which data was missing (all questionnaires had data missing). The average imputed value for each missing data point was calculated from those 20 imputations using the merge_imputations() function from R package sjmisc (Lüdecke, 2018). This average value was then used as the value for that missing data point, and total subscale scores for each questionnaire were then calculated from the imputed data set.

Behavioral Measures

Waiting for Information Task

The main curiosity task used willingness to wait for information as a measure of curiosity. Participants read trivia questions and choose whether to wait for the answer, or skip ahead to the next answer. Previous studies using this task have found that self-reported curiosity is a strong predictor of waiting (Kang et al., 2009; Marvin & Shohamy, 2016). The task lasted for 10 minutes, during which time participants could wait for or skip as many questions as they wanted. They also had the option to choose "know", meaning they were sure they knew the answer. Choosing know also skipped immediately to the next question. Wait times were chosen randomly on each trial to be either 4, 8, 12 or 16 seconds, and the length of the wait was always known to the participant. After receiving an answer, participants rated whether it was worth the wait on a Likert scale from 1 (not at all worth it) to 5 (extremely worth it).

Trivia Rating Task

In a second task, participants read a different series of trivia questions (that did not appear in the waiting task) and explicitly provided curiosity ratings. The task consisted of 10 random questions, and participants were asked to rate their pre-answer curiosity and their post-answer satisfaction on scales from 1-100. Participants could also select "know" on this task and if they did they were not asked to make ratings.

Memory Test

One week after completing the study, participants were sent an invitation to complete a second task. In this task, they were given a surprise memory test for the answers to the trivia questions they had seen in the two trivia tasks. The test showed the question and participants were asked to type the answer. 382 participants completed the memory test, from which data from 371 were included in the final sample after data exclusion criteria for the main study session were applied.

Standardized Curiosity Scores

Trivia questions for the waiting and rating tasks were selected from a larger database of questions previously rated by a separate group of participants on MTurk (N=800, ages ranging from 18-75). Online participants rated their curiosity about the trivia questions on a continuous scale from 0 ("Not at all curious") to 100 ("Extremely curious"). Each question was rated by between 30 and 60 people. Ratings were then averaged for each question and z-transformed, providing a standard measure of how curious people tended to be about each question. Questions were selected from the larger database based on the following criteria: less than 25% of raters knew the answer; a standard deviation of less than 1 after Z scoring; and question length of less than 110 characters. This resulted in 384 questions, and each trial of the Waiting and Ratings task drew a question at random from this list.

Monetary Delay Discounting Task

To measure individual differences in participants' general willingness to wait for rewards, we used a variation on a delay discounting task (Koffarnus & Bickel, 2014). This version of the task was chosen because it is brief and responsive, adjusting values based on participants' responses to each question. In five trials, participants chose between taking 5 dollars today and 10 dollars at some point in the future (monetary rewards were hypothetical). The first trial always started with a delay of 3 weeks, and then adjusted based on participants' choices in order to identify the point at which they would switch between choosing the immediate and delayed option. From these choices, the task automatically calculates a value of k, or individual discounting parameter, where low values of k indicated low discounting (more willingness to wait), and high values of k indicate high discounting (less willingness to wait).

Trait Measures

We identified eight questionnaires measuring trait level curiosity and related constructs. Most of these consisted of separate sub-scales, which were treated as independent for the purposes of our analysis, resulting in sixteen separate scores.

Five Dimensional Curiosity Scale (FDCS):

A recent update to the Curiosity and Exploration Inventory (CEI, Kashdan et al., 2009b), this measure includes five subscales. Joyous Exploration measures preferences for new information and experiences, and a tendency to view information as a reward. Deprivation Sensitivity measures the tendency to seek information to resolve uncertainty. Stress Tolerance relates to the ability to cope with anxiety that arises from novelty to uncertainty. Social Curiosity measures the interest in the thoughts and behavior of others. Thrill Seeking measures the tendency to seek out pleasure and adventure, and to take risks (Kashdan et al., 2018).

Interest and Deprivation Curiosity Scale (ID):

A measure of interest-based (tendency to derive pleasure from new ideas) and deprivation-based (tendency to spend time and effort to get specific pieces of knowledge) curiosity (Litman, 2008).

Perceptual Curiosity Scale (PC):

Two subscales divided based on specific and diversive curiosity. Specific curiosity measures a tendency to investigate and engage with perceptual stimuli. Diversive curiosity relates to seeking and exploring a broad range of perceptual experiences, (Collins et al., 2004).

Need for Cognition Scale:

Measures the tendency to engage in and enjoy effortful and challenging cognitive activities (Cacioppo, Petty, Feinstein, & Jarvis, 1996).

Big Five Personality Inventory (BFI):

From the Big Five Inventory, we used the Openness subscale, which measures one's openness to new ideas and experiences, including aspects of curiosity and creativity, (John, O. P., Naumann, L.P. & Soto, 2008; John, O.P, Donahue, E.M., Kentle, 1991).

Need for Closure Scale:

A measure of discomfort with ambiguity and a desire for predictability and order (Roets & Van Hiel, 2011; Webster & Kruglanski, 1994).

Barratt Impulsiveness Scale (BIS):

A measure of impulsivity comprised of three subscales: Attentiveness (inability to focus on a task), Motor (tendency to act on the spur of the moment) and Non-Planning (lack of ability to plan or think ahead), (Patton, Stanford, & Barratt, 1995).

Adult ADHD Self Report Scale (ASRS):

A self-report measure of attention-deficit/hyperactivity disorder (ADHD) in adults. The long form (18 item) version was used, which produces continuous scores of ADHD symptom burden (Kessler et al., 2005).

Analysis

Behavior on Curiosity Tasks

We first analyzed the data from the three curiosity tasks using multilevel regression models to predict trial-level responses. For the waiting task, we removed trials where participants selected "know", and used a logistic model to predict choices to wait or skip, based on question curiosity, age and wait length. We constructed a second model to additionally assess the effect of individual levels of discounting on choosing to wait by adding log transformed k values as a subject level predictor. For curiosity ratings, we predicted trial-level ratings, again using age and question curiosity. For the memory task, we used a logistic model to predict whether an answer was remembered or forgotten, based on question curiosity, age, and the number of questions each person needed to remember, along with a fourth variable indicating whether the participant had left the experiment tab during a given trial. In piloting, we found that clicking away during the test positively predicted memory. Participants were explicitly told that their reward would not be based on their memory performance, but it is likely that participants who left the tab were doing internet searches for answers. To account for this, trials were assigned a 1 if the participant left the tab, and a 0 if not, so that the other coefficients would represent effects when there was no outside activity. All models included random intercepts for each participant and each trivia question, as well as random slopes for the effect of question curiosity by participant.

Factor Analysis of Questionnaire Data

Among the questionnaire measures, there were a number of overlapping items, and scores on the subscales were correlated with one another. We conducted a factor analysis to determine if a smaller number of latent variables could be extracted from the data set and used to predict curiosity related behavior. All 136 items from the 16 scales were used in this analysis. Only subjects who had scores for all sixteen scales were included, for a total of 648 individuals. Again, we followed the methods used in Gillan et al. (2016). We used an implementation of Cattell's Criterion (Cattell, 1966) test via the R package nFactors (Raîche, Walls, Magis, Riopel, & Blais, 2013) to determine the number of factors to select. This test analyzes the screeplot of eigenvalues to identify the inflection point at which it switches from vertical to horizontal. This test suggested a four-factor solution. We then used the factanal() function from the psych package (Revelle, 2019) in R to conduct the factor analysis, using oblique rotation (oblimin). Composite scores for each participant on each factor were generated from the results of the factor analysis using the Bartlett weighted least squares method.

Relating State and Trait Measures

We took two different approaches to test the relationship between behavior on the waiting task and trait measures. First, each questionnaire score was z-scored and entered into an independent multilevel logistic regression model predicting trial-level choices to skip or wait. Models were constructed using the glmer() function of the R package lme4 (Bates, Maechler, & Bolker, 2013), with p values calculated by the package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017). Besides the addition of the questionnaires, the models used were the same as the one described above for the waiting task, with main effects for question curiosity score for each question, the wait length for each trial, and participant age. This resulted in sixteen separate models. To control for multiple comparisons across all the regression models, we extracted the p-values from the main effect terms for each questionnaire, and used Holm's step-down procedure to adjust each value (Holm, 1979).

In the second approach, we entered participant scores on each of the four factors into separate logistic regression models, to test whether each composite score predicted willingness to wait. A fourth model was constructed to include main effects of all four factors, in order to compare the size of their effects.

Relationship between Curiosity and Age

As noted above, age was entered as a covariate into the regression models predicting willingness to wait, explicit curiosity ratings, and memory. We examined the main effect of age on each of these tasks. To determine the relationship between trait scores and age, we calculated linear correlations between scores on each scale and age, as well as between the four factor scores and age. We again used the stepdown procedure (Holm, 1979) to correct for multiple comparisons.

Results

What predicts waiting for information?

We first analyzed behavior on the waiting task to see what variables predicted willingness to wait. With "Know" and missed trials removed, participants waited for an average of 52.68% of questions (sd = 31.64%). There was a wide range of waiting behavior, with 35 participants wait for none of the questions, and 69 waiting for all of them. As a result, the number of trials completed during the 10 minutes varied widely, with a minimum of 25 trials and a maximum of 179 (M=62.39, sd=35.18). As expected, participants were more likely to wait for high curiosity questions than low curiosity questions (b=0.62, SE=0.03, z=19.33, p< .001, N=659), and less likely to wait if wait times were long (b=-0.28, SE=0.02, z=-17.00, p< .001, N=659). In a second model, we examined the effect of individuals' tendency to discount rewards on the delay discounting task. In order to test if one's willingness to wait for monetary rewards would predicting waiting for information, we added each participant's value of k as a main effect. Participants who were more patient (lower k values) were more likely to wait for answers (b=-0.09, SE=0.04, z=-2.29, p= 0.02, N=658).

Relationship between Waiting and Rating

Comparing the two curiosity tasks across participants, average curiosity ratings on the Ratings task were positively correlated with the proportion of questions waited on the Waiting task (r=0.36, df=657, p<.001). Within the rating task, participants' explicit ratings of their curiosity were positively predicted by the standardized question ratings (b=9.44, SE=0.43, t=21.87, p< .001, N=656), suggesting that these average ratings are a good measure of potential curiosity.

Memory Task

We then tested what predicts subsequent memory on the waiting task. On average, participants remembered 38.64% of answers after a week delay (*sd* = 20.05%). However, scores ranged from 0% to 100%. Participants were more likely to remember the answer for questions with a high level of curiosity (b=0.33, SE=0.06, z=5.19, p< .001, N=359), than a low level. Although the number of questions to be remembered varied across participants from 1 to 34 (M=19.47, sd=7.57), this did not predict subsequent memory (b=-.01, SE=.05, z=-.17, p=.86).

How do trait measures of curiosity relate to one another?

The factor analysis produced four separate factors based on the 137 questions across the 16 measures. Together, the four factors accounted for 42 percent of the variance, (Factor 1 = 16%, Factor 2 = 14%, Factor 3 = 8%, Factor 4 = 4%). The first factor was the largest and included almost all of the items from the scales related to epistemic, deprivation-based, perceptual and social curiosity, along with all of the items from the openness to experience scale

Table 3.1: Average factor loadings across trait-level scales

	Factor 1		Factor 2		Factor 3		Factor 4	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Five-Dimensional Curiosity Scale								
Joyous Exploration	**0.68**	0.07	-0.06	0.09	0.00	0.07	0.15	0.12
Deprivation Sensitivity	**0.59**	0.13	0.14	0.08	0.25	0.17	0.10	0.11
Stress Tolerance	0.02	0.03	**-0.47**	0.05	**-0.53**	0.06	0.13	0.05
Social Curiosity	**0.35**	0.14	0.18	0.14	0.20	0.02	0.17	0.03
Thrill Seeking	0.22	0.06	**0.39**	0.09	**-0.35**	0.11	**0.40**	0.05
Interest/Deprivation Scale								
Interest	**0.64**	0.02	-0.02	0.07	-0.04	0.09	0.01	0.03
Deprivation	**0.54**	0.05	0.19	0.09	0.14	0.05	0.14	0.05
Perceptual Curiosity								
Specific	**0.39**	0.04	0.08	0.04	0.11	0.03	0.12	0.04
Diversive	**0.38**	0.08	0.00	0.09	-0.08	0.07	0.17	0.09
Need for Cognition	**0.62**	0.11	-0.10	0.19	-0.12	0.08	-0.18	0.14
BFI: Openness	**0.51**	0.13	-0.03	0.11	-0.06	0.17	-0.05	0.14
Need for Closure	-0.05	0.07	0.07	0.18	**0.59**	0.21	0.07	0.13
Barratt Impulsiveness Scale								
Attentiveness	-0.03	0.17	**0.54**	0.08	0.00	0.09	-0.10	0.21
Motor	-0.01	0.11	**0.47**	0.27	-0.1	0.08	0.15	0.22
Non-Planning	**-0.27**	0.22	**0.32**	0.20	-0.15	0.17	-0.13	0.24
Adult ADHD Self Report Scale	0.03	0.07	**0.69**	0.07	0.06	0.06	0.00	0.15

Average loadings above .25 bolded for emphasis

and the need for cognition scale. This factor was labeled as “Curiosity and Exploration”. The second factor consisted of items from the three impulsivity subscales from the Barratt Impulsiveness Scale and all of the items from the Adult ADHD Self Report Scale, and so was labeled “Impulsivity”. The third factor consisted of the items from Need for Closure Scale, along with items from the Five-Dimensional Curiosity Scale Deprivation and Stress Tolerance Subscales related to feelings of frustration when not having enough information. This factor was labeled as “Intolerance for Uncertainty”. The final factor was the smallest, and included the five thrill-seeking items (four of which also loaded onto factor 2), and items from the impulsiveness, need for closure, and need for cognition, which related to seeking out new experiences and a tendency to not make plans. This factor was labeled "Adventurousness". For each measure, we calculated the average factor loading for each of the four factors, shown in **Table 3.1**.

Does trait curiosity predict willingness to wait?

Individual Models

Each questionnaire was entered into its own model predicting choices to skip or wait for trivia. After correcting for multiple comparisons, eight of the sixteen measures significantly predicted choices on the trivia task. Scores on the FDCS Joyous Exploration and FDCS Deprivation Sensitivity, both perceptual curiosity subscales, the interest subscale of the ID scale, openness to experience and need for cognition positively predicted choices to wait vs. skip. Scores on the motor subscale of the Barratt impulsiveness scale negatively predicted these choices. Estimates for the effects of each questionnaire are shown in **Table 3.2**.

Table 3.2: Effects of individual trait measures on willingness to wait for information

Measure	*B*	*se*	*z*	*p*	*p (adj)*	*N*
Five-Dimensional Curiosity Scale						
Joyous Exploration	**0.47**	**0.10**	**4.95**	**<.001**	**<.001**	**654**
Deprivation Sensitivity	**0.28**	**0.10**	**2.91**	**0.004**	**0.036**	**654**
Stress Tolerance	0.10	0.10	0.94	0.350	0.885	654
Social Curiosity	0.23	0.10	2.29	0.020	0.152	654
Thrill Seeking	-0.11	0.11	-1.00	0.320	0.885	654
Interest/Deprivation Scale						
Interest	**0.47**	**0.10**	**4.88**	**<.001**	**<.001**	**656**
Deprivation	0.19	0.10	1.88	0.060	0.303	656
Perceptual Curiosity						
Specific	**0.31**	**0.10**	**3.22**	**0.001**	**0.014**	**656**
Diversive	**0.36**	**0.10**	**3.68**	**<.001**	**0.003**	**656**
Need for Cognition	**0.34**	**0.10**	**3.52**	**<.001**	**0.005**	**652**
BFI: Openness	**0.35**	**0.10**	**3.62**	**<.001**	**0.004**	**656**
Need for Closure	0.10	0.10	1.05	0.290	0.885	652
Barratt Impulsiveness Scale						
Attentiveness	-0.21	0.10	-2.02	0.040	0.263	659
Motor	**-0.32**	**0.11**	**-2.86**	**0.004**	**0.038**	**659**
Non-Planning	-0.25	0.10	-2.59	0.010	0.078	659
Adult ADHD Self Report Scale	-0.17	0.10	-1.61	0.110	0.426	653

Tests with adjusted p values less than .05 bolded for emphasis

Factor Models

We then calculated a score for each participant on each of the four factors based on their scores for each item within the factor. These scores were entered into a series of models predicting choices to wait and skip with the same set up used for the individual questionnaire models. The first four models included each factor alone, and a fifth included main effects of all four factors. In the individual models, Factor 1, Curiosity and Exploration, positively predicted choices to wait for answers b=0.43, SE=0.10, z=4.52, p< .001, N=645. For Factor 2, Impulsivity, higher scores decreased the chances of choosing to wait b=-0.25, SE=0.11, z=-2.34, p= 0.02, N=645. High scores on the third factor, Intolerance of Uncertainty, also positively predicted choosing to wait, but the effect was not significant b=0.15, SE=0.10, z=1.55, p= 0.12, N=645. Finally, Factor 4, Adventurousness, had a small negative effect on waiting, but this was also not significant b=-0.14, SE=0.10, z=-1.35, p= 0.18, N=645. Combining all four factor scores into one model then allowed us to compare the size of each of the effects. In this model, the Curiosity and Exploration factor was the largest, with a one standard deviation increase in scores on factor 1 corresponding to a 61% increase in the odds of waiting. The Impulsivity and Closure factors had similar effect sizes in opposite direction. A one standard deviation increase in Impulsivity score corresponded to a 22% decrease in the odds of waiting, while a one standard deviation

Table 3.3: Effects of latent factors on willingness to wait for information

Factor	***B***	***se***	***z***	***p***	***N***
Individual Models					
1. Curiosity and Exploration	**0.43**	**0.10**	**4.52**	**<.001**	**645**
2. Impulsivity	**-0.25**	**0.11**	**-2.34**	**0.02**	**645**
3. Closure	0.15	0.10	1.55	0.12	645
4. Adventurousness	-0.14	0.10	-1.35	0.18	645
Combined Model					
1. Curiosity and Exploration	**0.48**	**0.10**	**4.91**	**<.001**	**645**
2. Impulsivity	**-0.24**	**0.11**	**-2.28**	**0.02**	**645**
3. Closure	**0.27**	**0.10**	**2.81**	**<.001**	**645**
4. Adventurousness	-0.18	0.10	-1.86	0.06	645

Tests with p<.05 bolded for emphasis

increase in Closure score corresponded to a 31% increase. In the combined model, the effects for the first three factors were all significant. An increase in Factor 4, Adventurousness, predicted a 61% decrease in the odds, but this effect did not pass the .05 threshold for significance. Coefficients for all models are shown in **Table 3.3.**

How does Curiosity Change with Age?

We next looked across the different measures of curiosity to evaluate how they change with age. In the willingness to wait task, older participants were more likely to wait than younger ones (b=0.48, SE=0.10, z=4.95, p< .001, N=659). This was true even in the model that controlled for differences in discounting rates (b=0.45, SE=0.10, z=4.61, p< .001, N=658), suggesting that the age-related increase was not explained by an increase in willingness to wait in general. On the ratings task, there was a small positive effect of age, such that older participants made higher ratings of curiosity, but this effect did not reach the threshold for significance (b=1.31, SE=0.74, t=1.78, p= 0.08, N=656). The subset of participants who completed the memory test included a full range of ages, from 20 to 73. In this group, age positively predicted memory. Older participants were more likely to remember answers than younger ones (b=0.11, SE=0.05, t=2.39, p= 0.02, N=359), with a one standard deviation increase in age corresponding to a 13% increase in the odds of remembering.

For the trait measures, we tested the correlations between age and scores on all scales and factors. All r values were relatively small, with the largest around .3. However, after correction for multiple comparisons, age showed significant negative correlations with all three impulsiveness subscales, ASRS score, and the thrill seeking and social curiosity measures on the Five-Dimensional Curiosity Scale. There was a positive correlation with the Stress Tolerance subscale, indicating more stress tolerance with age. No other measures showed a significant relationship with age, including the measures of epistemic, perceptual and deprivation-based curiosity and openness to experience. Correlations with factor scores showed complementary results: scores on Factors 2 (Impulsivity) and Factor 4 (Adventurousness) decreased with age, but Factors 1 and 3 showed no relationship. Correlation results for each measure and shown in **Table 3.4**.

Table 3.4: Correlations between trait-level measures and age

Measure	*r*	*p*	*p (adj)*
Five-Dimensional Curiosity Scale			
Joyous Exploration	0.00	0.899	1.000
Deprivation Sensitivity	-0.08	0.045	0.405
Stress Tolerance	**0.23**	**<.001**	**<.001**
Social Curiosity	**-0.20**	**<.001**	**<.001**
Thrill Seeking	**-0.24**	**<.001**	**<.001**
Interest/Deprivation Scale			
Interest	0.01	0.801	1.000
Deprivation	-0.10	0.007	0.070
Perceptual Curiosity			
Specific	0.07	0.070	0.560
Diversive	-0.04	0.301	1.000
Need for Cognition	0.11	0.006	0.066
BFI: Openness	0.06	0.101	0.707
Need for Closure	0.00	0.905	1.000
Barratt Impulsiveness Scale			
Attentiveness	**-0.24**	**<.001**	**<.001**
Motor	**-0.26**	**<.001**	**<.001**
Non-Planning	**-0.13**	**0.001**	**0.012**
Adult ADHD Self Report Scale	**-0.24**	**<.001**	**<.001**
Factor Scores			
1. Curiosity and Exploration	0.01	0.750	1.000
2. Impulsivity	**-0.30**	**<.001**	**<.001**
3. Intolerance of Uncertainty	0.01	0.887	1.000
4. Adventurousness	**-0.14**	**<.001**	**<.001**

Tests with adjusted p values less than .05 bolded for emphasis

Discussion

In this study, we examined the relationship between trait curiosity and behavior on a curiosity task that required participants to wait for answers to questions they wanted to know. Results showed that state curiosity during the task was positively predicted by multiple trait level judgements, including epistemic, perceptual, and deprivation-based curiosity, need for cognition and openness to experience. We used an exploratory factor analysis to identify latent constructs within the sixteen personality measures, which revealed four factors. One, which encompassed almost all of the curiosity measures, positively predicted waiting for answers. The second, which was a combination of items related to impulsivity, negatively predicted waiting. The third factor, representing intolerance of uncertainty and need for closure, had a small positive effect on waiting when controlling for the other factors. The final factor, adventurousness, had a small negative effect on waiting, but this effect was not significant.

While factor 1 had the most explanatory power in this study, we found the lack of discrimination between different curiosity subscales surprising. There has been much debate in the literature over the best way to classify different dimensions of curiosity. Although numerous constructs have been differentiated, they are often assumed to be hierarchical and overlapping (Grossnickle, 2016). The pattern in our data fits with other research on trait curiosity, which has differentiated between cognitive or intellectual curiosity and stimulation and thrill seeking (Byman, 1993, 2005; Reio, Petrosko, Wiswell, & Thongsukmag, 2006). Also, we restricted our factor analysis to four factors based on the results of the CNG test, but testing models with more factors may lead to more separation between the different curiosity dimensions. Regarding the overlap between curiosity and to other trait dimensions in factor 1, different constructs may be the result of parallel lines of research in different fields that should be integrated rather than differentiated. For example, one study found a low degree of discriminative validity between measures of epistemic curiosity, need for cognition, intellectual engagement and openness to ideas (Mussel, 2010).

For this study, we chose to focus on a specific behavioral task that had previously been used in curiosity research. The trait curiosity measures we chose were predictive of willingness to wait on this task, but future research should investigate how the relationship between state and trait curiosity might differ for other behavioral tests of curiosity. For example, we found that impulsivity negatively predicted curiosity, but this may be related to the fact that acquiring information in this task also requires patience. Gambling tasks, in which participants trade monetary rewards for non-instrumental information about outcomes, have been able to tease apart independent effects of expected value and uncertainty reduction. Kobayashi et al. (2019) found no relations between behavior on their task and trait-level curiosity, but did show preliminary evidence for a relationship between trait risk tasking and individual differences in sensitivity to changes in value. Trait level characteristics may have different effects for different tasks, so it may be informative to investigate their impact on behavior in other measures of curiosity, like gambling, free-viewing and other exploration tasks.

While it is informative to understand how trait and state curiosity are similar, we should also consider where they diverge. When we examined the effects of age across all the experimental measures, we found age-related increases in willingness to wait on the behavioral task, even after controlling for age-related differences in temporal discounting. On the trait level measures, we observed a high degree of stability across ages on measures related to curiosity and exploration, which were encompassed by factor 1, with the exception of the social curiosity subscale, which decreased. Levels of intolerance of uncertainty, represented by factor 3, also showed no changes with age. On the other hand, trait impulsivity declined with age (factor 2), as did adventurousness (factor 4). This study was not longitudinal, but these results are consistent with the findings by Giambra (1992), which showed stability of curiosity scores both cross-sectionally and longitudinally, but significant age-related decreases in stimulation seeking. Overall, the lack of age-related decreases in curiosity in our data is at odds with the predictions made by Sakaki and colleagues (Sakaki et al., 2018), that curiosity would decline with age due to changes in dopaminergic functioning and reward processing.

The age-related increases in willingness to wait were accompanied by increases in memory performance, with older adults even outperforming younger ones on the memory test. Given that memory functioning tends to decline with age, these data underscore the importance of understanding the power of curiosity during old age. Increased curiosity may be a hallmark of successful aging (Sakaki et al., 2018), and it has previously been shown to be an important driver of memory in older adults (McGillivray et al., 2015; Metcalfe et al., 2015). Given its relationship to life satisfaction, well-being and even mortality on the trait level (Kashdan & Steger, 2007; Kawamoto et al., 2017; Swan & Carmelli, 1996), understanding the importance of curiosity in healthy aging may be an important factor in interventions to promote brain health and intellectual engagement in aging populations.

Understanding the relationship between trait and state curiosity also has important practical applications for education. Since curiosity can motivate learning and improve memory, harnessing it in the classroom can be an important driver of student success (Grossnickle, 2016; Oudeyer, Gottlieb, & Lopes, 2016). However, most of the research linking curiosity to academic achievement has been done at the trait level (Alberti & Witryol, 1994; Shah et al., 2018; van Schijndel et al., 2018a). Since trait level constructs are, by definition, relatively stable within individuals, state level curiosity is the best target for manipulations. Understanding how trait and state curiosity interact, as well as their changing relationship across development, may lead to better and more targeted curiosity-based interventions in classrooms.

Decades of research have produced many complementary understandings of curiosity. Trait research has shown the power of curiosity to affect our well-being, emotional health, intellectual engagement and even how long we live. Research on states of curiosity has shown how curiosity can drive memory, and has provided insight into the mechanisms of curiosity in relation to the brain's broader systems for processing reward. However, combining these two lines of work to test questions about how curiosity operates as both a trait and a state can only improve our ability to promote curiosity and benefit learning.

General Discussion

Across three studies, we used a combination of approaches to ask questions about how curiosity drives us to seek information. Combining data from behavior, brain imaging, eye tracking, and trait measures, these studies produced complementary results showing increased curiosity across ages, strong associations between curiosity and memory, and positive relationships between different measures of curiosity.

Curiosity and Reward

Given the findings from these three studies, we should consider where we stand on the information-as-reward framework for curiosity. Replicating previous work, we did find that the prospect of gaining information motivated behavior. Participants were willing to wait for information across all three studies, and their behavior was predicted by variables that we would expect to influence reward-seeking. They waited more for high value information (i.e. answers to questions that had high curiosity scores from previous raters), and waited less when the cost to attain the answer (the wait length) was higher. Participants were also more likely to remember the answers to high curiosity questions, replicating a well-established finding about the effects on memory of rewards in general, and curiosity specifically (Adcock et al., 2006; Gruber et al., 2014). Other tasks also fit this pattern. In the exploration task used in Chapter 2, participants were willing to spend time exploring hidden images even in the absence of a specific extrinsic motivation to do so.

The fMRI results from Chapter 1 also support this framework. Previous studies on curiosity in the brain had observed increases in activation in the mesolimbic reward circuits, particularly the striatum, in response to high vs. low states of curiosity (Bromberg-Martin & Hikosaka, 2009; Charpentier et al., 2018; Gruber et al., 2014; Kang et al., 2009). Here, we presented the first study to use the willingness-to-wait task in the scanner, and predicted that we would see similar patterns of activation when participants chose to wait for an answer compared to when they skipped it. This is, in fact, what the results showed; we observed higher levels of activation in the caudate when participants chose to wait instead of skip. Based on these data and the previous literature, it is clear that reward processing plays a role in curiosity. There are parallels in both behavior and brain data between the desire for information and the desire for extrinsic rewards.

Curiosity Across the Lifespan

However, the developmental data across all three studies does not provide evidence for a reward framework. If curiosity is based on the same underlying cognitive processes as other forms of reward seeking, then we predicted that it should be high in adolescents and low in older adults. While this fits with both previous theory on the topic (Sakaki et al., 2018) and conventional wisdom, it is not what we found. In the willingness to wait task, which was used in all studies with subjects ranging from 10 to 80, we found evidence for increased curiosity and better memory in older participants. Furthermore, we tested whether these age-related effects could be explained by differences in patience and willingness to wait in general, but this was not the case. In the other behavioral measures, we also found increasing curiosity in age. In our sample of adolescents and young adults, exploratory behavior in the visual exploration task increased with age, as did explicit ratings of curiosity for trivia questions. In the online study described in Chapter 3, trivia ratings also showed an increasing trend across age. For measures of trait curiosity in this sample, the trajectory across age was flat for multiple different curiosity trait scores, although related constructs like thrill-seeking and impulsivity declined with age.

These findings, from a large age range and across multiple measures, do not support the prediction that curiosity decreases with age.

This suggests that the study of curiosity should not focus solely on the parallels with reward processing. It may be possible that curiosity, while it involves reward systems, also draws on systems that do not show similar declines with age. For example, semantic processing has been shown to be remarkably stable with age, even as other forms of memory decrease (Luo & Craik, 2008; Umanath & Marsh, 2014b). General levels of semantic knowledge increase with age, and have also been shown to support memory encoding and retrieval throughout the lifespan (Brod et al., 2013). As outlined by Loewenstein (1994), curiosity may also rely on networks of prior knowledge, arising when we notice a gap that can be filled. One outstanding question regards whether semantic processing is necessary for all types of curiosity. Existing knowledge has a clear role when evaluating a trivia question, both in determining if you know the answer and understanding the context of the question. However, other forms of information seeking do not require deep semantic processing, such as curiosity about the outcome of a gamble. Future research should assess the extent to which semantic knowledge and memory are involved in different forms of exploration and knowledge seeking.

In order for curiosity to best support learning, it must incite goal-directed behavior. Another cognitive process that may be involved in curiosity is cognitive control. These systems are required for identifying what information is desired or needed, and initiating behavior that will help us pursue it (Cervera, Wang, & Hayden, 2020). The development of strategic information seeking has been studied during development. While children and adolescents are well known for both reward sensitivity and exploration, exploratory behaviors in young children tend to be random (Blanco & Sloutsky, 2019; E. Schulz et al., 2019; Sumner et al., 2019). With age, they learn to explore strategically, identifying options that are likely to be informative and figuring out how best to pursue them (Somerville et al., 2017). While this research was done in the context of reward learning, it is also relevant for information-seeking in the context of curiosity. Different behavioral measures of curiosity may draw on control processes in different ways. For example, simply self-reporting curiosity when you know an answer will appear afterwards requires little strategy. However, deciding how to best explore a hidden image to extract the most information in an efficient way, as in our visual exploration task, would require more control. This again emphasizes the importance of studying the influence of different cognitive processes across different forms of curiosity.

Convergent measures of curiosity

Research on curiosity encompasses four types of measurement. At the highest level, we can study self-reported trait curiosity, or a person's general tendency to be curious in a variety of domains (e.g. Collins, Litman, & Spielberger, 2004; Kashdan et al., 2018; Litman, 2008). We can also ask for self-reports of state curiosity, either in general or in response to a specific stimulus (e.g. Gruber, Valji, & Ranganath, 2014; McGillivray, Murayama, & Castel, 2015). Third, we can observe goal-oriented behavior, when people take action to obtain a specific piece of information (e.g. Lau, Ozono, Kuratomi, Komiya, & Murayama, 2018; Marvin & Shohamy, 2016). Finally, we can observe open-ended exploration, when there is no specific target but people sample information from the environment in a self-directed way (e.g. Daffner, Scinto, Weintraub, Guinessey, & Mesulam, 1994; Gross, Araujo, Zedelius, & Schooler, 2019). Generally, research has focused on these approaches to curiosity one at a time, and although there is work on the relationship between trait and state curiosity (Kashdan & Steger, 2007;

Litman et al., 2005), we know relatively little about how these different measures relate to one another.

We utilized multiple measures of curiosity which tap into these different dimensions. In two studies, we found positive associations between behavioral measures of state curiosity. In Chapter 2, willingness to wait, exploratory behavior and self-reported curiosity ratings were all positively correlated with one another. In Chapter 3, willingness to wait was predicted by higher explicit curiosity ratings. Furthermore, willingness to wait in Chapter 3 was predicted by the self-reported trait measures related to epistemic, deprivation-based and perceptual curiosity, but not by related constructs like social curiosity and thrill-seeking. While most research on trait curiosity has relied on questionnaires, the convergence of our behavioral measures points to a second potential way to quantify a person's overarching tendency to be curious, which aligns with trait measures but does not rely on self-report.

Limitations

Studying development and aging is difficult, and while these data show differences across ages, the cross-sectional nature of the designs cannot allow us to conclude that curiosity changes with age within individuals. While this is possible, another explanation could be that people that are highly curious tend to age more successfully than those who are not, and maintain essential cognitive abilities longer. This idea is supported by a study that longitudinally followed a group of adults starting in their seventies, and found that high trait curiosity at the first time point predicted subsequent longevity (Swan & Carmelli, 1996). In order to participate in research studies, participants must be relatively healthy, both physically and mentally, so it is important to consider the possibility that our sample was biased towards older adults who were highly curious but not representative. Future research should examine whether increased curiosity is a natural consequence of increasing age, or whether it is specifically a hallmark of successful aging.

While we tried to consider and control for cognitive processes that might influence curiosity, such as temporal discounting, there are many other factors that could be involved in how we pursue information. One example is emotion and valence. Taking the perspective that information can serve as a reward naturally frames curiosity as a positive experience. However, this need not always be the case. One study found that while people are willing to pay for information about positive outcomes, they were also willing to pay to avoid getting information about negative ones (Charpentier et al., 2018). However, in studies of morbid curiosity, participants have been found to actively seek out information that is unpleasant, and these decisions can also recruit brain circuits related to reward (Oosterwijk, 2017; Oosterwijk, Snoek, Tekoppele, Engelbert, & Scholte, 2019). How might curiosity for negative or unpleasant information change with age? One hallmark of the aging process is a general bias in both attention and memory towards positive stimuli (Mather & Carstensen, 2005). We found increased curiosity in older adults using trivia questions, and finding out answers to such questions is usually an enjoyable experience. By focuses on this type of curiosity, we cannot say how desire for more unpleasant information might change with age. Information valence has been shown to impact curiosity (Marvin & Shohamy, 2016), so future research should investigate whether curiosity in older adults generalizes to many types of information, or if it is biased specifically towards positive information.

Future Directions

Future research should investigate the role that different sources of uncertainty play in curiosity. In tasks like the ones used here, information is always attainable. Participants are asked to judge if the information is worth pursuing, but they always know they can get it if they want to. This is not usually how information seeking works in real-world situations. A simple question may be answered by a quick google search, but other questions may require may require much more research, or may not be attainable at all. Studies using gambling tasks have begun to investigate this, by using risky gambles that may or may not pay off (Lau et al., 2018), or not awarding information for every trial (van Lieshout et al., 2018). Future studies could test how changes in this kind of uncertainty might influence choices to pursue information and to explore, as well as how these decisions change with age.

Curiosity obviously has many applications for education. Trait curiosity has been linked to educational achievement (Alberti & Witryol, 1994; Shah et al., 2018; van Schijndel et al., 2018a), and researchers have sought ways to promote curiosity in the classroom (Grossnickle, 2016; P. Y. Oudeyer, Gottlieb, & Lopes, 2016). Laboratory studies on curiosity often study it by taking advantage of stimuli that are inherently interesting, like trivia questions. However, it is also important to understand how curiosity about a neutral stimulus could be increased or decreased, since not all information that needs to be learned is interesting. This was part of our motivation in developing the visual exploration task used in Chapter 2. If curiosity can be measured by the amount of exploration a participant engages in, we can test different interventions to try to increase or decrease curiosity. The task described here included one such manipulation, in the form of the "hints" that appeared before each trial. Participants were briefly shown a small or large amount of information about what they would be exploring, and we found that they explored more when they had seen less, and explored the most when they had had no hints at all. We have begun work on new studies using this task that test other variables, including the participants' ability to choose what to explore, the presence and absence of hints, and the amount of information conveyed in these hints. Future work with this task not only allows us to study open-ended exploration as a form of curiosity, but also provides the opportunity to test interventions that can promote or discourage exploration.

Conclusion

Curiosity is an important driver of learning and exploration. Many of our everyday decisions are guided simply by the desire to know and understand. Curiosity has important implications for education, but also for our well-being, health and happiness (Kashdan & Steger, 2007). In this research, we have tried to shed light on the cognitive processes that underlie curiosity by studying it across the lifespan. A better understanding of how curiosity is sparked and how it translates into exploratory behavior may help us to develop new ways to harness curiosity for learning from childhood to old age.

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General Introduction

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