The wick in the candle of learning: Epistemic curiosity activates reward circuitry and enhances memory

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ABSTRACT

Curiosity has been described as the "wick in the candle of learning" but its underlying mechanisms are not well-understood. We scanned subjects with fMRI while they read trivia questions. The level of curiosity when reading questions is correlated with activity in caudate regions previously suggested to be involved in anticipated reward or encoding prediction error. This finding led to a behavioral study showing that subjects spend more scarce resources (either limited tokens, or waiting time) to find out answers when they are more curious. The fMRI also showed that curiosity increases activity in memory areas when subjects guess incorrectly, which suggests that curiosity may enhance memory for surprising new information. This prediction about memory enhancement is confirmed in a behavioral study— higher curiosity in the initial session is correlated with better recall of surprising answers 10 days later.

Keywords: Neuroimaging, Memory, Learning, Brain

Curiosity is the complex feeling and cognition accompanying the desire to learn what is unknown. Curiosity can be both helpful and dangerous. It plays a critical role in motivating learning and discovery, especially by creative professionals, increasing the world's store of knowledge. Einstein, for example, once said, "I have no special talents. I am only passionately curious (Hoffmann, 1972)." The dangerous side of curiosity is its association with exploratory behaviors with harmful consequences. An ancient example is the mythical Pandora, who opened a box that unleashed misfortunes on the world. In modern times, technology such as the Internet augments both good and bad effects of curiosity, by putting both enormous amounts of information and potentially dangerous social encounters a mouse click away.

Despite its importance, the psychological and neural underpinnings of human curiosity remain poorly understood. Philosophers and psychologists have described curiosity as an appetite for knowledge, a drive like hunger and thirst (Loewenstein, 1994), the hunger pang of an 'info-vore' (Biederman & Vessel, 2006), and "the wick in the candle of learning" (William Arthur Ward). In reinforcement learning a "novelty bonus" is used to motivate the choice of unexplored strategies (Kakade & Dayan, 2002). Curiosity can be thought of as the psychological manifestation of such a novelty bonus.

A theory guiding our research holds that curiosity arises from an incongruity or 'information gap'—a discrepancy between what one knows and what one wants to know (Loewenstein, 1994). The theory assumes that the aspired level of knowledge increases sharply with a small increase in knowledge, so that the information gap grows with initial learning. When one is sufficiently knowledgeable, however, the gap shrinks and curiosity falls. If curiosity is like a hunger for knowledge, then a small "priming dose" of information increases the hunger, and the decrease in curiosity from knowing a lot is like being satiated by information.

In the information-gap theory, the object of curiosity is an unconditioned rewarding stimulus: unknown information that is anticipated to be rewarding. Humans (and other species, such as cats and monkeys) will expend resources to find out information they are curious about, much as rats will work for a food reward (Loewenstein, 1994). Based on this observation, we hypothesized that the striatum would be linked to curiosity since a growing body of evidence suggests that activity in the human striatum is correlated with a value prediction error that guides valuation (Hare, O'Doherty, Camerer, Schultz, & Rangel, 2008), which in most studies is highly correlated with primary and secondary rewards (Knutson, Westdorp, Kaiser, & Hommer, 2000; McClure, York, & Montague, 2004; O'Doherty, 2004).

Guided by the ideas mentioned above, we explored the neural correlates of curiosity in one study and tested the hypotheses derived by its findings in two separate studies. In all studies, subjects were presented with series of trivia questions chosen to create a mixture of high and low "epistemic" curiosity (Fig. 1a). Subjects read each question, guessed the answer, and rated their curiosity and how confident they were that they knew the answer (*P*). Then they were shown the question again followed by the correct answer (Fig. 1b).

In the first experiment subjects read the questions during fMRI. In the second experiment they performed the same task without scanning, and their memory for answers was tested in a follow-up session 1-2 weeks later. In the third experiment, we behaviorally tested whether curiosity is indeed a form of reward anticipation.

EXPERIMENT 1

Method

Participants and Task

Nineteen Caltech students were scanned (average age: 21.7 ± 3.5 years; 14 males; 18 right-handed). They earned $20 for participation. Informed consent was obtained for all three experiments, using a consent form approved by the Internal Review Board at Caltech. The stimuli used in the task are 40 trivia questions on various topics, designed to measure curiosity about semantic knowledge and pre-tested to evoke a range of curiosity levels (for sample questions, see Fig. 1a). After reading each question, participants were instructed to silently guess the answer, and to indicate their curiosity about the correct answer and the confidence they had in their guess. Then they saw the question presented again, followed by the correct answer (for a timeline and details of curiosity and confidence ratings see Fig. 1bc).

fMRI Acquisition and Analysis

Data were acquired using a 3-T Siemens (Erlangen, Germany) Trio scanner at Caltech. A set of high-resolution ($0.5 \times 0.5 \times 1.0$ mm^3) T1-weighted anatomical images was first acquired to enable localization of functional images. Whole-brain T2*-weighted echoplanar (EPF) images with BOLD contrast were acquired in 32 axial slices (64 x 64 voxels; in plane resolution $3 \times 3 \times 3$ mm^3 slices) at TR of 2000 msec, TE of 30 msec. The scan sequences were axial slices approximately parallel to the AC-PC axis. The fMRI data were preprocessed using SPM2 (Welcome Department of Imaging Neuroscience, Institute of Neurology, London, UK). Functional scans were first corrected for slice timing correction via linear interpolation. Motion correction of images was performed using a 6-parameter affine transformation followed by nonlinear warping using basis functions (Ashburner & Friston, 1999). Finally, images were smoothed with a Gaussian kernel of 8mm FWHM. The data analysis was conducted using the random effects GLM for event-related designs in SPM2.

1. Curiosity median split analysis: All trials were split by the individual median curiosity level. Then all five epochs in each trial (1^{st} presentation, curiosity rating, confidence rating, 2^{nd} presentation, and answer display) were associated with either a high or low curiosity condition according to the median curiosity. Two conditions for each epoch were generated, resulting in a total of 10 separate regressors of interest. Each regressor was time-locked to stimulus presentation. A GLM including these 10 regressors plus regressors of no interest was estimated. We then calculated contrasts to compare the effects of high vs low curiosity.

2. Curiosity interaction analysis: We further examined whether the brain activations identified in the previous analysis were increasing with curiosity level. We estimated a GLM in which each of the 5 epochs has normalized curiosity as a parametric modulator.

3. Residual curiosity analysis: This analysis was performed to investigate the effect of curiosity that is dissociated from *P* and *P(1-P)*, and the interaction between curiosity and correctness, on learning. First, we regressed curiosity on *P* and *P(1-P)* (with a constant), and then took the residuals from this regression to construct a new variable, called the "residual curiosity". Second, to examine the effect of the interaction between the residual curiosity and correctness of guess on learning, the answer display epoch was divided into correct/incorrect guess conditions, resulting in a total of 6 conditions of interest: 1^{st} presentation, curiosity rating, confidence rating, 2^{nd} presentation, answer display preceded by a correct guess, and answer display preceded by an incorrect guess. We then estimated a GLM in which each of these 6 conditions has *P*, *P(1-P)*, and the residual curiosity as parametric modulators.

Results

Curiosity is correlated with uncertainty P(1-P) and peaks around confidence P=.5

The information-gap theory predicts that curiosity should increase with statistical uncertainty *P(1-P)* (since people who know very little haven't had their curiosity piqued, and those who know a lot are satiated). Reported curiosity is indeed an inverted U-shaped function of *P*, with maximum curiosity when *P* is around 50% (Fig. 1c). The correlation coefficient between curiosity and *P(1-P)* is $r = .44$, $p < 0.0005$. Most subjects showed this relation; estimated peak curiosity to *P* was between .45 and .55 in three-quarters of the subjects.

Analyses of brain activity first focus on activity when *questions* are initially presented, and then focus on activity when *answers* are presented. All analyses identify activity in regions across the entire stimulus presentation, using the BOLD signal. Results are reported for brain areas that are significant at uncorrected *p*-value of 0.001 (unless noted as $p < 0.005$) and cluster size $k \geq 5$.

Curiosity is correlated with activity in reward regions

The first question presentation epoch was associated with either a high or low curiosity condition according to the individualized median curiosity level. We created a contrast that identified regions whose activity was greater in response to high curiosity than to low curiosity. Significantly activated regions include the left caudate, bilateral prefrontal cortex (PFC) and parahippocampal gyri (PHG) (Table 1). Activations in the putamen (x,y,z=21,9,9), $t(18) = 3.15$, and the globus pallidus (x,y,z=12,-6,0), $t(18) = 3.94$, were significant at $p<0.005$ (uncorrected), but no activation was found in the nucleus accumbens. Activation in the left caudate which is significant in the high-low curiosity median split overlaps with activity in that region when the regressor is either the subject-normalized linear curiosity or the residual curiosity (Fig. 2b). This finding is consistent with the view of curiosity as anticipation of rewarding information.

Curiosity is correlated with memory-related regions when incorrect answers are revealed

When the answer was revealed, activations were much stronger in response to incorrect than correct answers, in areas linked to learning and memory. Areas differentially activated when subjects guessed incorrectly, compared to when guessed correctly, included the bilateral putamen and left IFG (Broca's area) (Fig. 3a).

The curiosity level modulates the activations shown in the previous analysis. Conditional on an incorrect guess, left PHG and left IFG activations were positively correlated with the residual curiosity during answer display (Fig. 3b). The left IFG is dorsal to areas observed in the question epoch (recall Fig. 2a) and is part of Broca's area, which is important for language comprehension (Bookheimer, 2002). However, when subjects guessed correctly, the residual curiosity did not correlate with any of the regions above.

Because memory-related regions are differentially activated in response to incorrect answers, and the activity is modulated by curiosity, we hypothesized that curiosity would be associated with “memory enhancement” for new information—in our paradigm, a correct answer is new information when initially guessed incorrectly. Conditional on guessing incorrectly, people will be more likely to remember the answer to a question if they were curious to know it.

The findings from the fMRI study led to the ideas that curiosity is anticipation of rewarding information and that it may also enhance learning of new information. We tested these hypotheses in separate experiments. We first describe an experiment to test the memory-enhancement hypothesis and then another experiment to test the reward anticipation hypothesis.

EXPERIMENT 2

Method

Participants and Task

Sixteen Caltech students (11 males) participated. The task and timeline were identical to Experiment 1 except for some minor changes; full randomization of questions across the experiment, no fixation screens, fixed 10 sec question presentation, and visible count-down of 5 sec before answer. Measured variables were identical to Experiment 1 except that subjects' guesses were recorded (as a check on post-scanner over-reporting of correct guesses in Experiment 1, which was minor).

Upon completing the task, subjects were unexpectedly asked to return within 11-16 days for a follow-up study. Twelve returned in about 2 weeks and were used in the analysis. Subjects were then shown the same questions, asked to recall the correct answers (earning $.25 for each correct answer), in addition to $15 for participation.

Measures

Behavioral measures were the same as in experiment 1. A new measure is whether they recalled the correct answer in the follow-up session.

In the initial session, pupil dilation response (PDR) before and after the answer display was also recorded using a Mobile Eyelink II eyetracker (SR Research, Osgoode, Ontario) at 250 Hz. Experiments were conducted and analyzed in Matlab (Mathworks, Inc., Natick, MA) using the Psychophysics Toolbox (Brainard, 1997) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002). Blinks were treated as missing data and removed. We focused on the time interval 4.8 sec before to 4.8 sec after the answer onset. After normalization, we split the pupillary data collected over this interval into high, middle, and low-curiosity level groups. Then the data were averaged every 400 msec across subjects (Fig. 4a).

Results

Pupils dilate in response to curiosity-piquing questions

Trials were divided into three terciles based on curiosity measured in the initial session. When the subjects were more curious about the answer, PDR responses ramped up 1~2 secs before the answer onset, peaked 800 msec after, then dropped back to baseline around 2 sec afterwards (Fig. 4a). Average PDR during anticipation (1 sec before the answer onset) was significantly higher for high curiosity items compared to middle curiosity items ($p < 0.03$, one-tailed t-test), and modestly different for middle compared to low curiosity items ($p = 0.13$, one-tailed t-test). When the answer appeared (0~1000ms after the onset), the average PDR was significantly different among all three groups ($p < .03$ or lower).

Initial curiosity enhances subsequent memory for incorrectly guessed answers

In the follow-up session 1-2 weeks later, curiosity expressed in the initial session had a strong effect on recall of the answers to the questions that were initially guessed incorrectly (Fig. 4b). The differences in accuracy rate between high vs. middle, middle vs. low, and high vs. low, were all significant at $p < 0.05$ (paired one-tailed t-tests), in support of the hypothesis that higher curiosity levels lead to better recollection. The same analysis with residual curiosity and including control variables (P and $P(1-P)$) also shows a main effect of curiosity on recall. Consistent with the fMRI findings, these suggest that curiosity activates memory regions differentially in response to surprising (wrong) answers, resulting in higher accuracy rates in the memory test.

EXPERIMENT 3

Method

Participants

This follow-up experiment consisted of two conditions: A token condition (10 Caltech students, 23.4±3.3 years, 5 males); and a time condition (20 Caltech students, 19.9±2.2 years; 12 males).

Task and Measures

The task and timeline were like Experiment 1 and 2 except for two features: (1) subjects had to spend scarce tokens or time, to learn answers; and (2) 10 questions were added to the original 40 questions. A reward is an object or event that elicits approach and is worked for (Wise, 2004). Requiring subjects to spend tokens or time measures their willingness to pay for information they are curious about. The different conditions test robustness to the type of resource which is spent.

In the token condition, subjects had to spend one of their 25 experimental tokens to find out the answer to a question. Subjects read each question, reported their curiosity and confidence levels, and typed their guess. After guessing, they could pay one token to see the answer immediately. The tokens did not have cash value, but since there were 25 tokens and 50 questions, spending a token on one answer meant skipping another answer. Based on the experiment 1 finding that high curiosity is correlated with activity in the striatal region, we hypothesized that when subjects are more curious they anticipate higher reward from learning information, so they will spend tokens when they are curious. Other results are possible. They could allocate tokens based on confidence, impatiently use all their tokens in the beginning, alternate spending, or exhibit some other pattern unrelated to curiosity.

The second condition imposed a different cost: After guessing, subjects had to wait until the answer appeared. Subjects were told the waiting time distribution (uniform from 5-25 seconds). Subjects could quit waiting and skip to the next question at any time. We hypothesized that subjects would be more likely to spend time, waiting longer, for the answers that they were more curious about.

Results

The logistic regressions show that spending tokens or time are both strongly correlated ($p<0.001$) with curiosity (Fig. 5). The significance did not change when P and $P(1-P)$ were included, or when residual curiosity was used. At the individual-subject level, correlations between curiosity and spending were significant at $p<.01$ for 28 of 30 subjects. Subjects wait for an additional 3.7 seconds as their normalized curiosity level increases by one standardized unit.

DISCUSSION

In turn-of-the-century psychology, curiosity was considered an important drive, but research on it subsequently waned (Loewenstein, 1994). This study attempts to revive interest in curiosity, measuring it by self-report, and studying neural correlates of reported curiosity with fMRI. The findings suggest hypotheses about memory and reward anticipation.

The correlations between reported curiosity and lateral PFC and caudate activity are consistent with the information-gap hypotheses that curiosity is linked to anticipation of information, and that information is a secondary reinforcer. Curiosity is correlated with activity in the caudate when a question is first presented. The caudate is an area well-established to be involved in reward anticipation/reward learning over a wide variety of primary and secondary reinforcers (Delgado, Locke, Stenger, & Fiez, 2003; Delgado, Nystrom, Fissell, Noll, & Fiez, 2000), including social rewards (King-Casas et al., 2005 ; Rilling et al., 2002), and reaction to unexpected rewards (Berns, McClure, Pagnoni, & Montague, 2001) and prediction error (Hare et al., 2008).

Previous studies have found that caudate can be activated by expecting feedback per se (Aron et al., 2004). Our experimental design has feedback because answers are given. If there is brain activity in anticipation of positive feedback, it should be modulated by the confidence level *P*—the more confident you are in being right, the more positive feedback you would expect. The parametric design of the analysis (correlating activity with curiosity levels, and then with residual curiosity) precludes the possibility that the caudate activation was driven solely by expectation of feedback from accurate guesses (because residual curiosity and confidence are uncorrelated by construction). Activity in left PFC is also consistent with the idea that curiosity is associated with an intrinsic value of learning because neurons in left PFC receive input from neurons in the substantia nigra via the dorsal striatum, which respond to primary rewards and reward-prediction, show sustained phasic activations during reward expectation (Watanabe, 1996), and whose activity is modulated by magnitude of reward (Leon & Shadlen, 1999; Rogers et al., 1999).

There are also studies which report striatal activations in response to negatively valenced stimuli (Knutson, Adams, Fong, & Hommer, 2001) or in non-reward activity such as working memory and motor preparation (Cairo, Liddle, Woodward, & Ngan, 2004; Simon et al., 2002). Since our task did involve working memory and motor preparation, the striatal activation we found could be due to increased attention or "incentive salience" or other activities (as some studies suggest). Given that people tend to be more attentive to an object that is rewarding, the fMRI evidence alone cannot separate the attention or salience interpretations from reward anticipation.

Therefore, the reward anticipation interpretation was investigated further in a separate behavioral study. In Experiment 3, subjects were allowed to either spend a token or wait to see the answers to questions of their choice. Both actions incur a cost—a lost opportunity, or lost time. People are generally willing to spend time and resources to obtain objects that they find rewarding. This enhanced willingness to spend more resources to find out more curiosity-provoking question answers is consistent with the reward interpretation and not with interpretations that the fMRI results indicate only attention or incentive salience.

Recent computational neural network models suggest another compatible interpretation involving memory (Frank, Loughry, & O'Reilly, 2001; O'Reilly & Frank, 2006). Question stimuli trigger differing levels of curiosity and depending on the curiosity level, the basal ganglia sends out a signal to enable the lateral PFC to update, maintain, and internally represent information associated with a higher level of curiosity, whose answer may be anticipated to be more rewarding. This internal representation in lateral PFC, particularly in left IFG, is a crucial component of long-term memory consolidation and learning of new information (Paller & Wagner, 2002).

PHG and left IFG are activated in response to wrong answers, modulated by high curiosity. These regions are thought to be involved in successful verbal memory encoding (Brewer, Zhao, Desmond, Glover, & Gabrieli, 1998; Paller & Wagner, 2002; Wagner et al., 1998). In conjunction with the caudate and left PFC activations in the first presentation, this activity suggests the hypothesis that curiosity strengthens memory of correct answers when subjects were initially wrong— i.e., that curiosity is linked to reward value of information (or learning-based prediction error) and also enhances learning from new information.

This conjecture led to Experiment 2 measuring PDR and memory. Since pupil dilation is known to be linked to arousal, attention, interest, cognitive effort (Beatty, 1982; Hess & Polt, 1960) more efficient verbal learning (Kahneman & Peavler, 1969), and anticipatory pupillary responses increase following a stimulus that predicts rewards (O'Doherty, Dayan, Friston, Critchley, & Dolan, 2003), the correlation of curiosity with pupil dilation is consistent with both reward anticipation and learning of novel information. The enhancement of later recall of novel information by curiosity suggests that curiosity helps to consolidate novel information in memory. Having established that curiosity is a form of reward anticipation, we can also tie this research to the work of Adcock, Thangavel, Whitfield-Gabrieli, Knutson, & Gabrieli, (2006) who showed that anticipated monetary rewards modulate activations in the mesolimbic and parahippocampal regions and promotes memory formation prior to learning. Our result complements theirs by showing that *endogeneous* internal motivation manifested in curiosity recruits similar neural circuits that are recruited by *exogenous* incentives, and both have a similar effect on learning.

We also found bilateral putamen activation during the answer display in response to incorrect guesses. Although no explicit reward or punishment was involved, subjects might have perceived guessing incorrectly as an unexpected inherent punishment (with varying degrees of anticipation based on confidence). The differential putamen activations we found might reflect this "internal punishment" aspect of guessing incorrectly and the saliency of the event since subjects received new piece of information (in contrast, when guessing correctly, nothing new was revealed). This interpretation is consistent with the recent finding that unexpected punishments produce very similar BOLD responses in the putamen as unexpected rewards at the time of outcomes (Knutson et al., 2000; Seymour, Daw, Dayan, Singer, & Dolan, 2007).

The exploratory nature of our study does not allow us to examine all possible aspects of curiosity separately. It is certainly likely that curiosity works differently in different sensory and knowledge domains. The trivia questions we used evoke what is often called "specific epistemic curiosity" (Berlyne, 1954). This kind of curiosity is the desire for a particular piece of information and is often associated with motivations for academic achievement and scientific discovery. This type of curiosity is probably different from the sensation driven by stimulus novelty or the desire to avoid boredom or sensory deprivation. The latter type of curiosity is called diversive perceptual curiosity and can be found in various animals (Berlyne, 1954). The curiosity we measured includes a desire to learn new information, and anticipation of the rewarding information to be learned (because subjects received feedback). A study without feedback would isolate pure curiosity absent anticipation and learning (but would not permit study of the response to right and wrong answers).

Further studies could also show whether curiosity is different for visual stimuli, semantic narratives like page-turner novels, social information like gossip, and “morbid curiosity”.

Understanding the neural basis of curiosity has important substantive implications. Note that while information-seeking is generally evolutionarily adaptive (Panksepp, 1998), modern technologies magnify the amount of information available, and hence the potential effects of curiosity. Understanding curiosity is also important for selecting and motivating knowledge workers who gather information (such as scientists, detectives, and journalists). The *production* of engaging news, advertising and entertainment is also, to some extent, an attempt to *create* curiosity. The fact that curiosity increases with uncertainty (up to a point), suggests that a small amount of knowledge can pique curiosity and prime the hunger for knowledge, much as an olfactory or visual stimulus can prime a hunger for food, which might suggest ways for educators to ignite the wick in the candle of learning.

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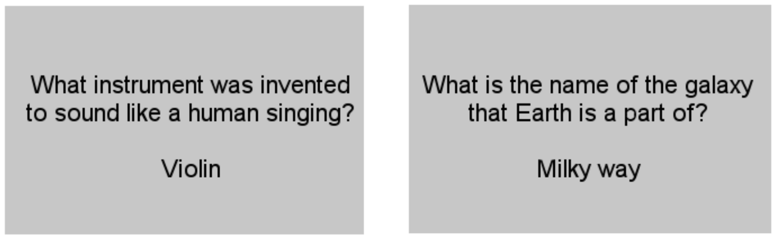
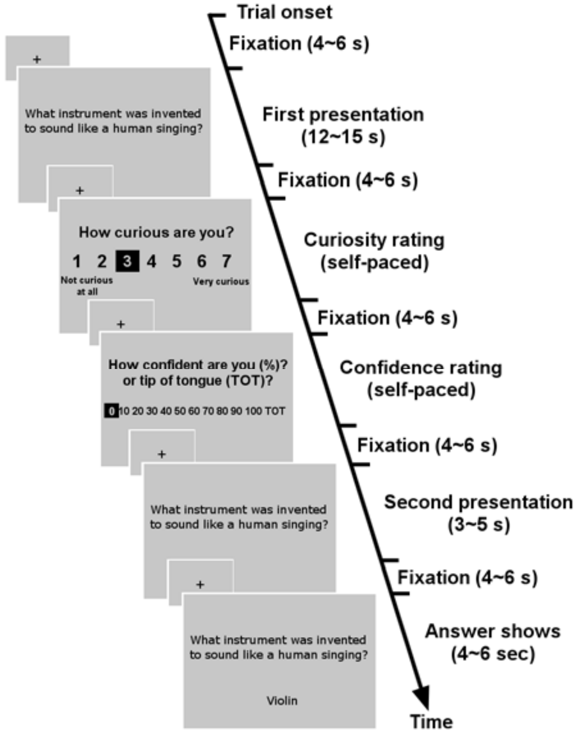

What instrument was invented to sound like a human singing?
Violin
What is the name of the galaxy that Earth is a part of?
Milky way

b


Trial onset
Fixation (4~6 s)
First presentation (12~15 s)
Fixation (4~6 s)
Curiosity rating (self-paced)
Fixation (4~6 s)
Confidence rating (self-paced)
Fixation (4~6 s)
Second presentation (3~5 s)
Fixation (4~6 s)
Answer shows (4~6 sec)
Time
+
What instrument was invented to sound like a human singing?
How curious are you?
1 2 3 4 5 6 7
Not curious at all
Very curious
How confident are you (%)? or tip of tongue (TOT)?
0 10 20 30 40 50 60 70 80 90 100 TOT
Violin

c

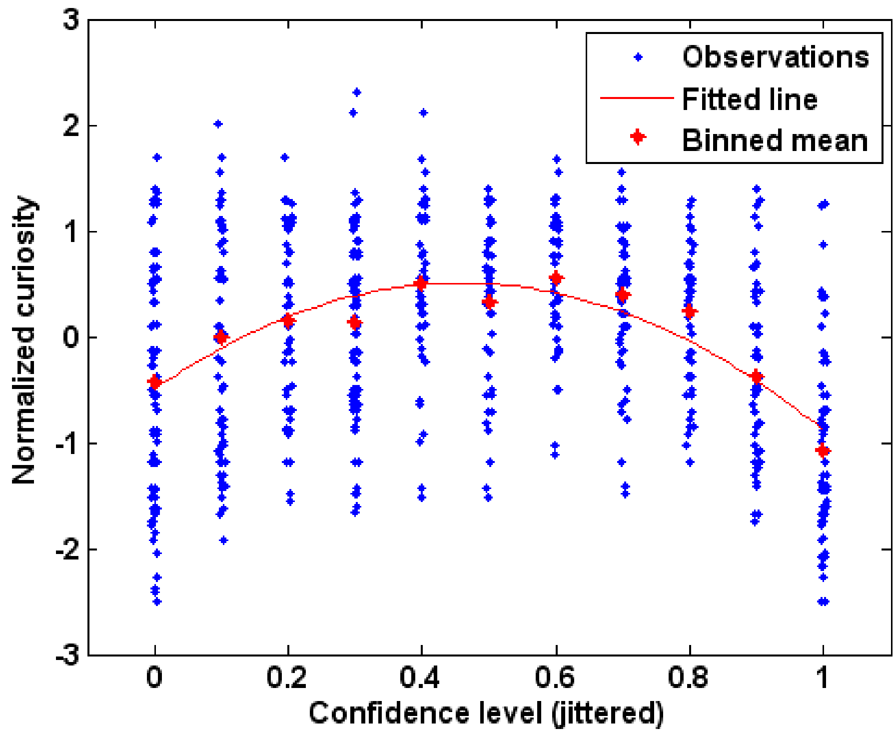


Fig. 1. Experimental protocol and behavioral results. (a) Sample questions with relatively high (*Left*: average 5.72 out of 7) and low (*Right*: 2.28 out of 7) curiosity ratings. (b) Task timeline. (c) Distribution of curiosity against confidence: The confidence scale ranged from 0 to 100% but was rescaled to range from 0 to 1. There was also a tip of the tongue (TOT) response option (Maril, Wagner, & Schacter, 2001) but there were too few of these responses to analyze so they were excluded. All confidence ratings are jittered by adding random numbers U~[-0.005, 0.005] to convey data density. Raw curiosity ratings 1-7 and were normalized for each individual (subtracting each individual's mean and dividing by each individual's standard deviation). Red stars indicate mean curiosity at each confidence level. The solid curve line is the regression line of curiosity against confidence P and uncertainty $P(1-P)$. The estimated regression is Curiosity = -0.49 – 0.39P + 4.77$P(1-P)$ + Residual curiosity.

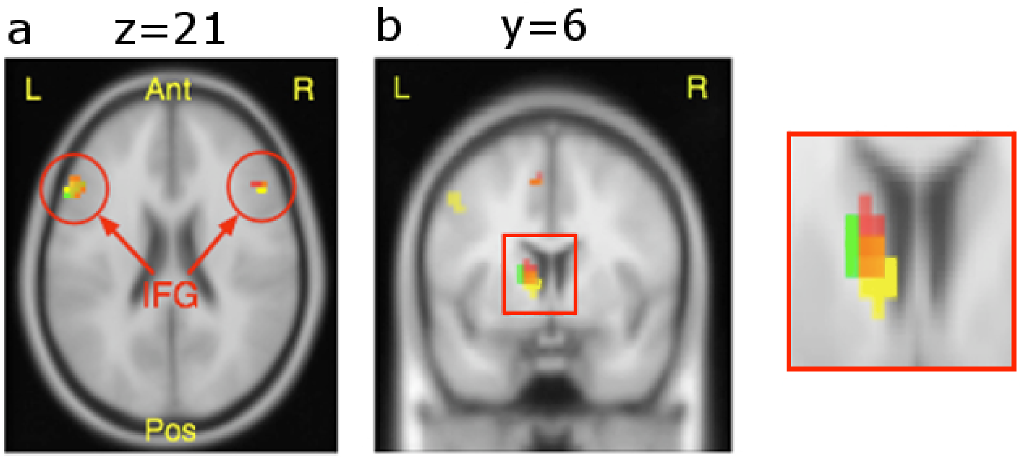


Fig. 2. Differential brain activity in high and low curiosity trials during first question presentation. (All results *p*<.001 uncorrected, extent threshold ≥5.) (a,b) Overlapped regions of activation in bilateral PFC by curiosity from three different dependent variable models: High > Low median-split curiosity (red); linear in curiosity (yellow); linear in residual curiosity from the Fig. 1c regression (green). Note that we did not find activation in OFC regions as one might expect, but this is not surprising because our sequence was not optimized to detect OFC activations. (Right) Overlapped close-up of caudate activations from the same three different models in (b).

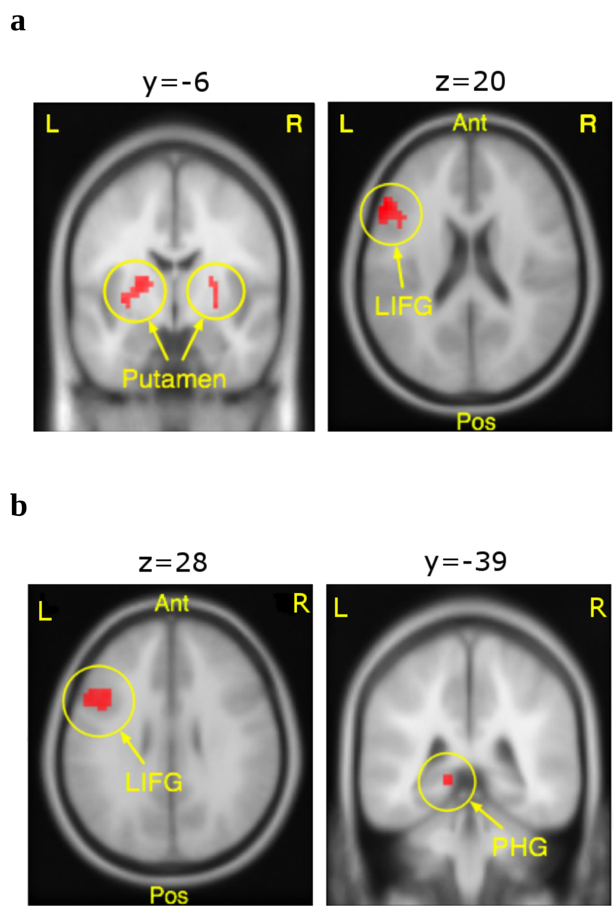
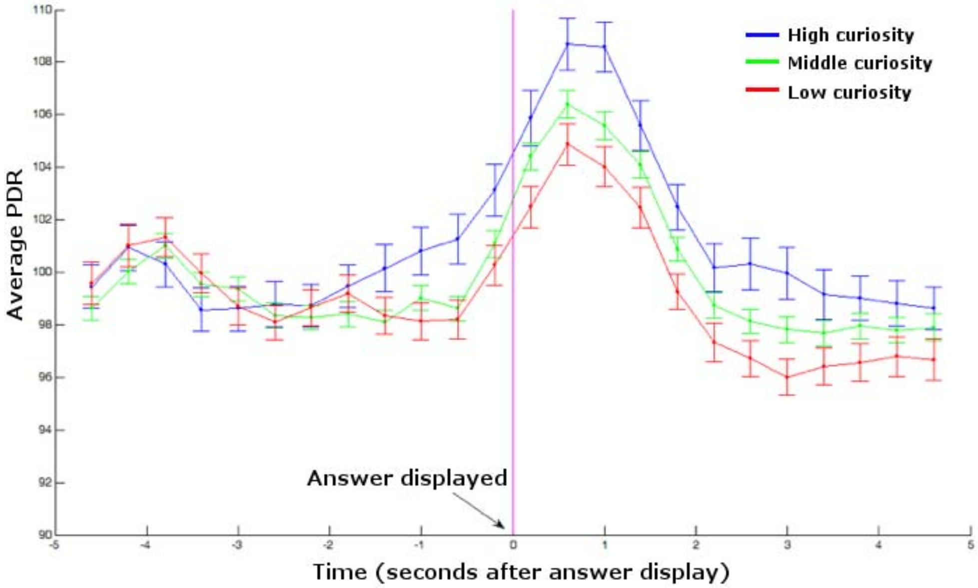


Fig. 3. Areas of differential brain activity during answer revelation. (a) Regions which are more active in response to wrong answers than to right answers: Bilateral putamen (right: *x*,*y*,*z*=-24,-9,6, *t*(18)=4.63; left: *x*,*y*,*z*=24,-9,12, *t*(18)=4.77), left IFG (Broca's area, BA 44/45).(b) Regions with activity correlated with novel information (wrong answers × curiosity). Left IFG (left), Left PHG (right). Bilateral midbrain regions (left: *x*,*y*,*z*=-12,-24,-6, *t*(18) = 3.37; right: *x*,*y*,*z*=12,-21,-18, *t*(18) = 3.97) and the hippocampus (*x*,*y*,*z*=-27,-33,-6, *t*(18)=3.2) (not shown) were also activated at $p<0.005$ (uncorrected).

a


High curiosity
Middle curiosity
Low curiosity
Average PDR
110
108
106
104
102
100
98
96
94
92
90
Answer displayed
-5
-4
-3
-2
-1
0
1
2
3
4
5
Time (seconds after answer display)

b

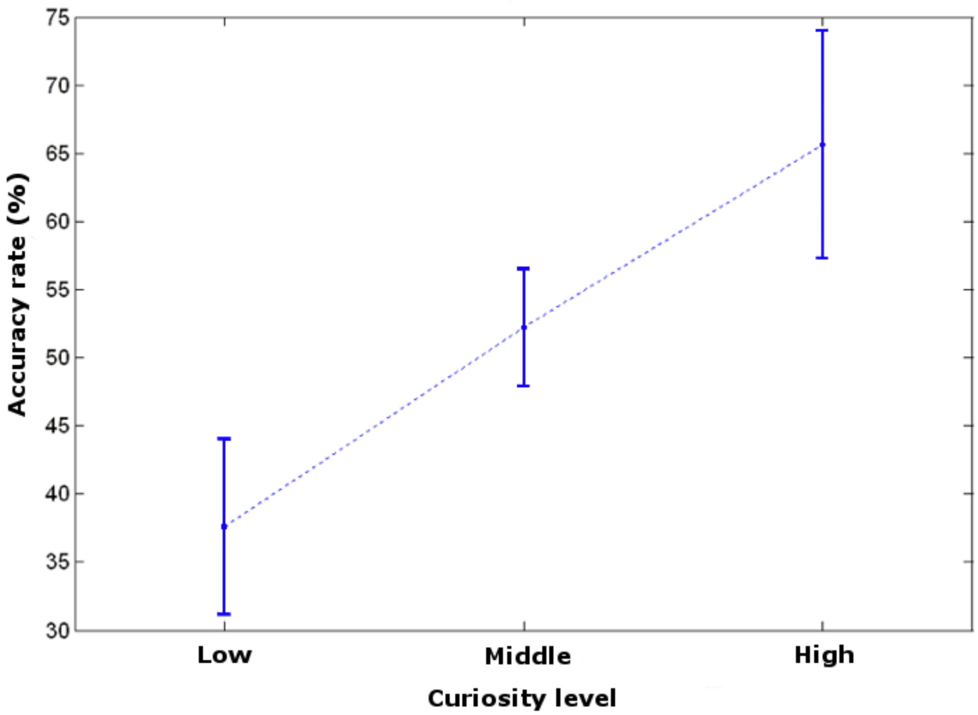

Accuracy rate (%)
75
70
65
60
55
50
45
40
35
30
Low
Middle
High
Curiosity level

Fig. 4. Experiment 2: Pupillary Response and Memory Test. (a) Pupillary response: Curiosity correlates with pupil dilation before and just after answers are revealed. Y-axis shows individually normalized pupil dilation (n=16) for high (blue) (above the 67th individual percentile), middle (green) (in between), and low (red) (below the 33rd individual percentile) curiosity trials, around answer revelation (time 0). The average pupil dilation in this time interval for each subject was normalized to 100. (b) Memory test: Focusing only on the questions subjects initially guessed wrong, we again divided the questions into three (high/middle/low) curiosity groups. Then the average accuracy rate (the number of correct recalls divided by the number of total answers to be recalled) was computed for each group across subjects.

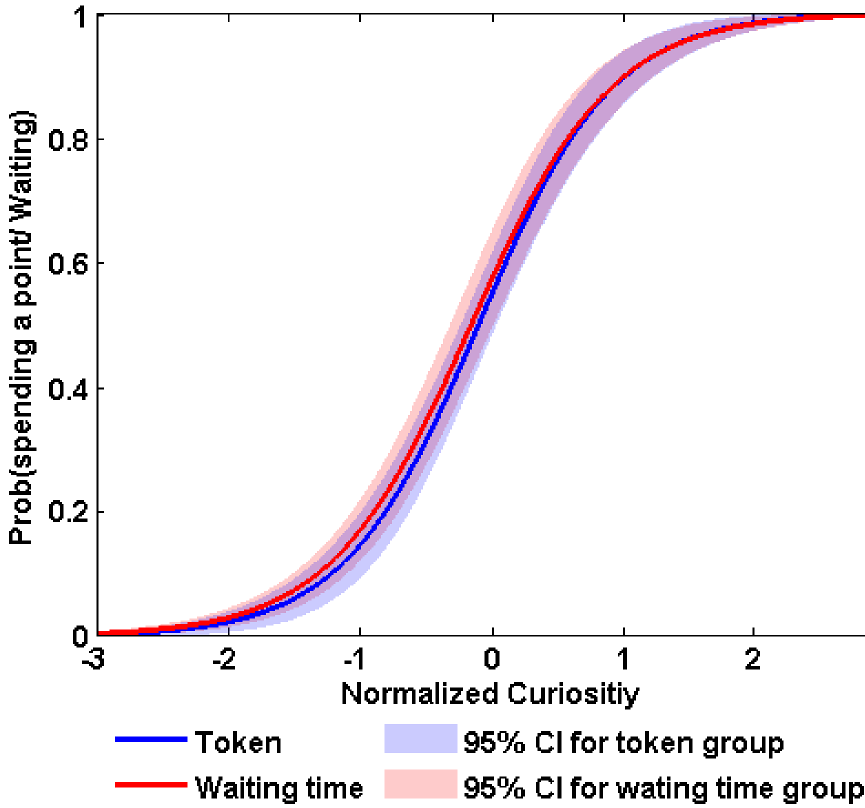


Fig. 5. Experiment 3: Curiosity correlates with willingness-to-pay the cost. Group logit curves relating normalized curiosity to the probability of spending a token (*blue*) or waiting time (*red*) to learn the answer to a trivia question. Logistic regression analyses were performed to test whether curiosity is correlated with spending tokens or time. For each condition, we pooled the data across subjects. The dependent variables, whether to spend a token (=1) or to spend assigned waiting time (=1), were regressed on a subject-normalized curiosity rating and a constant. Three separate analyses were also performed subject-by-subject, including *P* and *P(1-P*), and using length of waiting time in an OLS regression. C.I.=confidence interval.

TABLE

Table 1. Brain regions associated with high curiosity relative to low curiosity during the first presentation

Region	L/R	Coordinates			Spatial Extent	t
		x	y	z	(voxels)	
Caudate	L	-9	3	3	10	4.04
IFG/BA45	L	-54	24	21	112	5.71
	R	48	24	21	5	4.01
PHG	L	-33	-39	-12	21	4.04
	R	36	-30	-18	5	4.46
Medial Frontal Gyrus	L	-12	36	48	26	4.49
MFG, Pre-motor Cortex	L	-27	15	57	70	5.71
Lingual gyrus	R	18	-63	-3	11	4.57
Cerebellum	R	36	-69	-36	34	4.67

All locations are reported in MNI coordinates.

Supporting Information for

The wick in the candle of learning: Epistemic curiosity activates reward circuitry and enhances memory

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This document includes:

Supplementary Methods, Analysis, and Results
Supplementary Figures
Supplementary Tables
Supplementary Materials

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Contents

Debriefing Sheets
Post Curiosity Memory Test Instructions
Questionnaire

SUPPORTING METHODS

Participants

Experiment 1: Initially, 20 subjects participated. One subject was discarded because he received instructions in the scanner instead of outside, and showed odd behavioral data – his median curiosity rating was “7”, the maximum allowed, not creating enough variation in curiosity across questions.

Experiment 2: Sixteen Caltech students completed the first task. Out of the 16 participants, one did not return. Two returned within one week and had too high recall rate (90%) and one returned in 3 weeks, and the data from these three participants were not used for memory analysis reported in the manuscript.

Experiment 3: Initially, 21 subjects participated in the waiting time condition, but one subject was excluded for further analysis because his data showed that he was not engaged in the task—first, he did not take enough time to comprehend a question (he spent only 2.1 sec, which is a third of the time that the other 20 subjects spent reading a question on average) and secondly, his curiosity and confidence ratings were highly correlated with anchor ratings (70% and 65%, respectively), which means that he submitted anchor ratings instead of his own.

Experimental Procedure.

Experiment 1: Written instructions were administered outside the scanner. Once subjects understood the experimental procedure, they were put in the scanner for the task. Each experimental session consisted of 4 runs, with each run containing a set of 10 questions, which were randomly presented within each run. There was a one minute break between runs, due to physical restrictions on the scanner. One question cycle consisted of 5 epochs: first presentation of a question, curiosity rating, confidence rating, second presentation, and answer display. The duration of each epoch was randomized within a certain range (Fig. 1b). The task was presented to subjects through MRI compatible goggles. Subjects were given 12 to 15 seconds to read the question, followed by a fixation screen displayed for 4 to 6 seconds. The curiosity and confidence rating epochs were self-paced; the subjects moved on to the next screen by making their selection with an MRI-compatible button box. These rating screens were also followed by fixation cross screens. Then the question was presented again for 3 to 5 seconds, and then the answer was revealed below the question for 4 to 6 seconds. To keep the motor requirement of the task minimal, the presentation of questions and answers were not designed to be self-paced. Each of these cycles took about a minute, with the entire experiment lasting for approximately 45 minutes. Since verbal or typed responses were not easily available in the scanner, upon finishing the task the subjects self-reported their initial guesses at the correct answers to the questions and filled out a questionnaire, outside of the scanner.

Experiment 2: The experimental procedure was identical to that for the functional imaging study, except for a few modifications: (a) The order of questions was randomized across the entire 40-question trials, (b) Fixation screens were removed (they were necessary in fMRI to allow the BOLD signal to dissipate between decision epochs, but unnecessary in a behavioral study), (c) The first presentation screen time was fixed at 10 seconds of exposure (rather than 12~15 seconds in the fMRI study), (d) A ‘count-down’ of five seconds was presented immediately before the answer showed in order to attract subjects’ attention and precisely quantify their pre-answer anticipation in pupil size, (e) Since there were few tip-of-the-tongue responses in the fMRI study the TOT option was removed from the confidence scale, (f) Between the curiosity and the confidence rating screens, a “give answer” screen was presented and subjects were asked to state their guess out loud so that an experimenter could record them.

Experiment 3: The task was identical to the previous experiments with two modifications. First, in this experiment, subjects had to spend some cost – either an experimental token or waiting time—to see the answer. Fig. S1 describes the detailed timeline of the task. Second, we were concerned that in the token condition some subjects might spend their tokens too quickly or too slowly, so that they would have either none left or many left before the last few questions. If so, their token choices in those later trials would not reflect their true desire for information. We therefore added 10 new questions at the end as padding and excluded them for the analysis, using only the same 40 questions used in Experiment 1 (including the last 10 does not change the results, however). Indeed, three of 10 subjects spent all their tokens and one of 10 subject shad sufficient tokens to see all 10 answers left by the time the last 10”padding” questions started. There is no budgeting problem in the time condition, so all 50 question trials were included in the analysis.

SUPPORTING ANALYSIS AND RESULTS

Functional Data Analysis and Results

In all imaging data analyses, the regressors were modeled using box-car functions, convolved with a canonical hemodynamic response function. All four runs were concatenated and treated as one run and to control for the variance between sessions from concatenation, session dummy variables were included as separate regressors. Images were adjusted for both global intensity, using proportional scaling; and for low-frequency physiological drifts, using a high-pass filter of 128 secs. Autocorrelation of the hemodynamic responses was modeled as an AR(1) process. Parameters were estimates from a ReML procedure. We initially performed 19 separate single-subject analyses: voxel-by-voxel statistical parametric maps of the t-statistic for each contrast of interest were defined for each subject. These contrast maps were then integrated to derive contrast images for second-level group T-tests and ANOVA (Friston, Holmes et al. 1995; Ashburner, Neelin et al. 1997; Genovese, Lazaar et al. 2002).

The contrast, (1^{st} H > 1^{st} L), described in the manuscript, further shows putamen and globus pallidus activations at a more lenient p-value of 0.005 (uncorrected) (Fig. S3B). Fig. S4 presents the time-course of hemodynamic responses in the caudate and lPFC during the first presentation. The caudate activation precedes that of the lPFC by a few seconds. In the opposite contrast, (1^{st} L>1^{st} H), we found small clusters of the cingulate gyrus (CG), the anterior CC, and the right middle frontal gyrus (MFG) at p<0.001.

Next, another contrast (2^{nd} H > 2^{nd} L), which was constructed in a similar manner to (1^{st} H > 1^{st} L), identified brain regions which were associated with high curiosity relative to low curiosity in the second presentation of the question (immediately preceding the revelation of the answer) (Table S10B). The only notable region at $p<0.001$ was the left lPFC. There were also anterior insula, ACC, and thalamus activations which were significant at $p<0.005$. The opposite contrast, 2^{nd} L>2^{nd} H identified a small area in the MFG at $p<0.001$.

In the 'residual curiosity' analysis, left caudate, insula, and lPFC activations were positively correlated with P in the 1^{st} presentation, while in the 2^{nd} presentation the activations were in the bilateral insula, and right caudate. The uncertainty *P(1-P)* is correlated with activity in bilateral parahippocampal gyri (PHG) during the first presentation of the question (Fig. S5A, Table S11). In the 2^{nd} presentation, only the right insula was significantly sensitive to *P(1-P)* at $p<0.001$ and the bilateral insula at $p<0.005$ (Fig. S5B, Table S11). Unlike the 1^{st} H > 1^{st} L contrast in the curiosity median split model, the parahippocampal gyrus activity was related not to residual curiosity, but to the *P(1-P)* in the 1^{st} presentation.

Conditional on a wrong guess, parahippocampal gyrus, DLPFC, and IFG activations were positively correlated with residual curiosity in the answer epoch at p<0.001 (Table S11A), with additional activations in the left and right midbrain regions at p<0.005 (Fig. S6A). We also tested for the interaction between curiosity and correctness in the answer epoch by creating the (Resid curio|Wrong > Resid curio|Right) contrast (Fig. S6BC). This contrast identifies brain areas which are more sensitive to curiosity when guessing incorrectly than when guessing correctly. At $p<0.001$, bilateral parahippocampal gyrus and left IFG activations were significant (Fig. S6C, Table S11B) and, at $p<0.005$, the same midbrain region as in Fig. S6A was significantly active (Fig. S6B).

There is also activity correlated with the *degree* of negative "surprise" in the answer epoch— i.e., areas which are active when people are wrong *and* more confident (the GLM regressor is a dummy variable for wrong answer condition × confidence P in the 'residual curiosity' analysis). The degree of negative surprise is correlated with anterior (ACg) and posterior cingulate (PCg) activity and with bilateral anterior Insula (Fig. S7), but there is no similar effect of positive surprise (a dummy for correct answer condition × *(1-P)*). The cingulate regions are known to be activated by tasks creating cognitive conflict such as Stroop tasks (Carter, Braver et al. 1998; Kerns, Cohen et al. 2004), which is sensible since a wrong answer creates conflict between the prior guess and the answer.

Pupillometric Data Analysis and Results

Ordinary least squares (OLS) regression analysis was performed to confirm the effects of curiosity on PDR, controlling for individual fixed effects and a quadratic time trend. The regression analysis shows that an increase of one standard deviation in curiosity level results in a 0.76% (standard error 0.34%) and 0.86% (0.35%) increase in average PDR during the anticipation and answer viewing, respectively (Table S4).

Memory Test Data Analysis and Results

Instead of using the raw curiosity rating as in the manuscript, we repeated the same procedure with the residual curiosity (as defined in the manuscript). Average accuracy rates are 56% (5.14%) for high, 51% (5.81%) for middle, and 38% (6.40%) for low curiosity questions (standard error in parenthesis) (Fig. S8). The difference in accuracy rate between high vs. middle was in the right direction but insignificant ($p=0.17$, paired one-tailed t-test), but the differences between middle vs. low and between high vs. low were significant ($p<0.04$ and $p<0.01$, respectively, paired one-tailed t-tests). The result is a little bit weaker, but still consistent with the previous results.

Both the OLS and the logit regression analyses were also performed to confirm the effects of curiosity on memory enhancement. The dependent variable, correct recall in the memory test (coded as 1 for a correct recall and 0 for an incorrect recall), was regressed on curiosity level interacting with two dummy variables that indicate whether subjects initially guessed the answer correctly or not. The regression analyses also find consistent evidence that curiosity modulates the later recall rate for answers to questions that subjects initially guessed incorrectly (Table S5).

Token-spending and Waiting-time Data Analysis and Results

Table S6 and S7 report the group logistic regression models described in Figure 5 of the text. Table S8 reports the results of the individual logistic regressions for the effects of normalized curiosity on the decision to spend a token or time. Figure S9 and S10 show the individually fitted probabilities of spending a token or time as a function of the normalized curiosity ratings, using the coefficients reported in Table S8. Additionally, we reported the likelihood-ratio test of two logistic regression models to see the effect of confidence *P* and uncertainty *P(1-P)* on the decision of whether to spend a token or time. The two models were first estimated subject-by-subject: the restricted model included only normalized curiosity as an independent variable while the unrestricted model additionally included *P* and *P(1-P)* as independent variables. Then we performed a likelihood-ratio test, testing whether the restricted model is significantly different from the unrestricted model—in other words, whether normalized curiosity (without *P* and *P(1-P)*) is enough to explain the choice data. Table S9 shows that for 23 subjects out of 30, adding *P* and *P(1-P)* does not improve the model fitness significantly. Further, for the 7 subjects who show significant improvement after adding *P* and *P(1-P)*, we compared the logistic regression model with only normalized curiosity to one with only *P* and *P(1-P)* as independent variable(s). For three subjects out of those 7, the model with normalized curiosity shows a better fit (higher pseudo-R^2) than the model with *P* and *P(1-P)*. In sum, for most of the subjects, curiosity is the strongest predictor of whether a subject will spend tokens or time to see the answer to a question.

Reference

Ashburner, J., P. Neelin, et al. (1997). "Incorporating prior knowledge into image registration." Neuroimage **6**: 344-354.

Carter, S. C., T. S. Braver, et al. (1998). "Anterior cingulate cortex, error detection, and the online monitorning of performance." Science **280**: 747-749.

Friston, K. J., A. P. Holmes, et al. (1995). "Statistical parametric maps in functional imaging: a general linear approach." Human Brain Mapping **2**(4): 189-210.

Genovese, C. R., N. A. Lazaar, et al. (2002). "Thresholding of statistical maps in functional neuroimaging using the false discovery rate." Neuroimage **15**: 870-878.

Kerns, J. G., J. D. Cohen, et al. (2004). "Anterior cingulate conflict monitorning and adjustments in control." Science **303**: 1023-1026.

SUPPORTING FIGURES

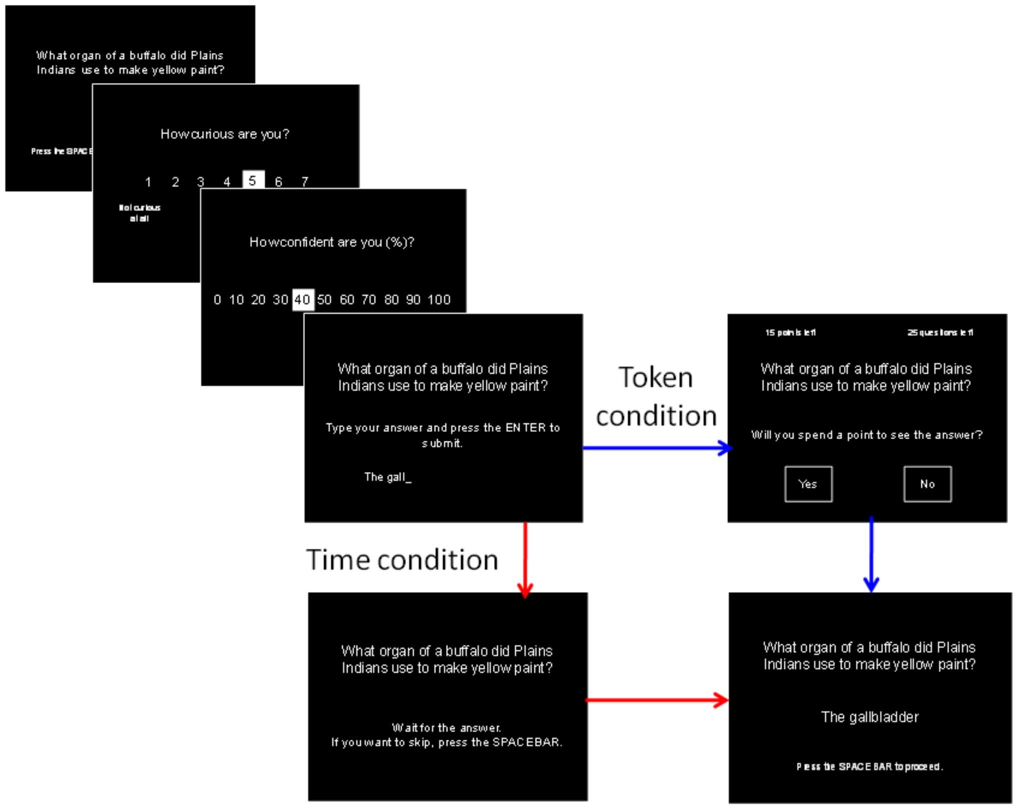
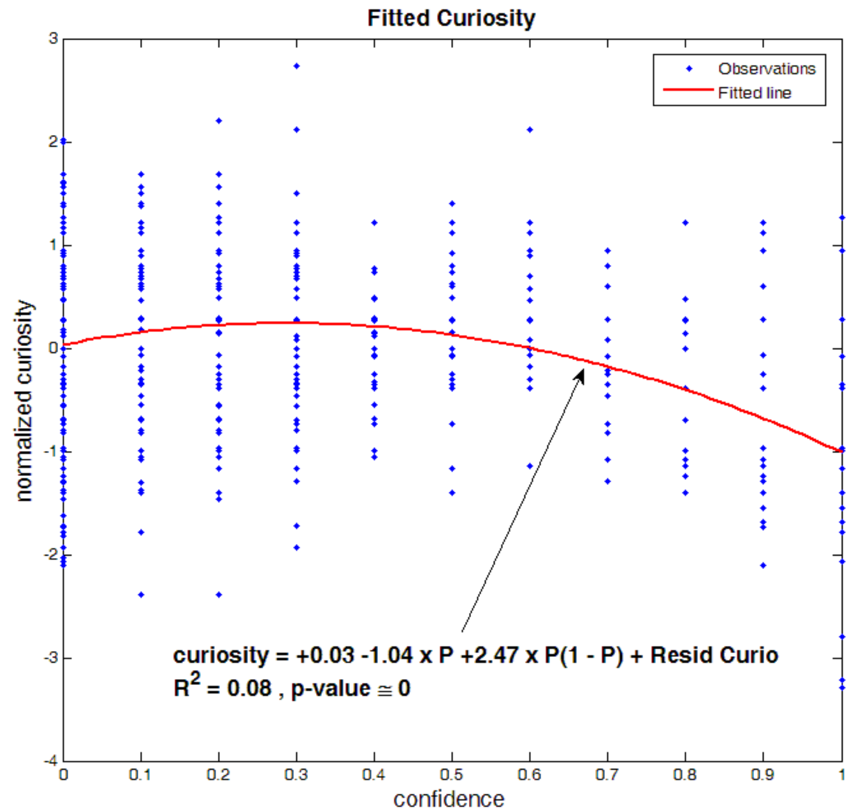


Figure S1: Timeline of Experiment 3. Subjects read a question, rate curiosity and confidence level about the answer and type their guess. Then subjects can either spend a token (in the token condition) or wait for a certain amount of time (in the time condition) to see the answer if they wish. If they don't want to see the answer, they can quickly move on to the next question.

(A)


Fitted Curiosity
Observations
Fitted line
normalized curiosity
confidence
curiosity = +0.03 -1.04 x P +2.47 x P(1 - P) + Resid Curio
R2 = 0.08 , p-value ≅ 0
3
2
1
0
-1
-2
-3
-4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

(B)

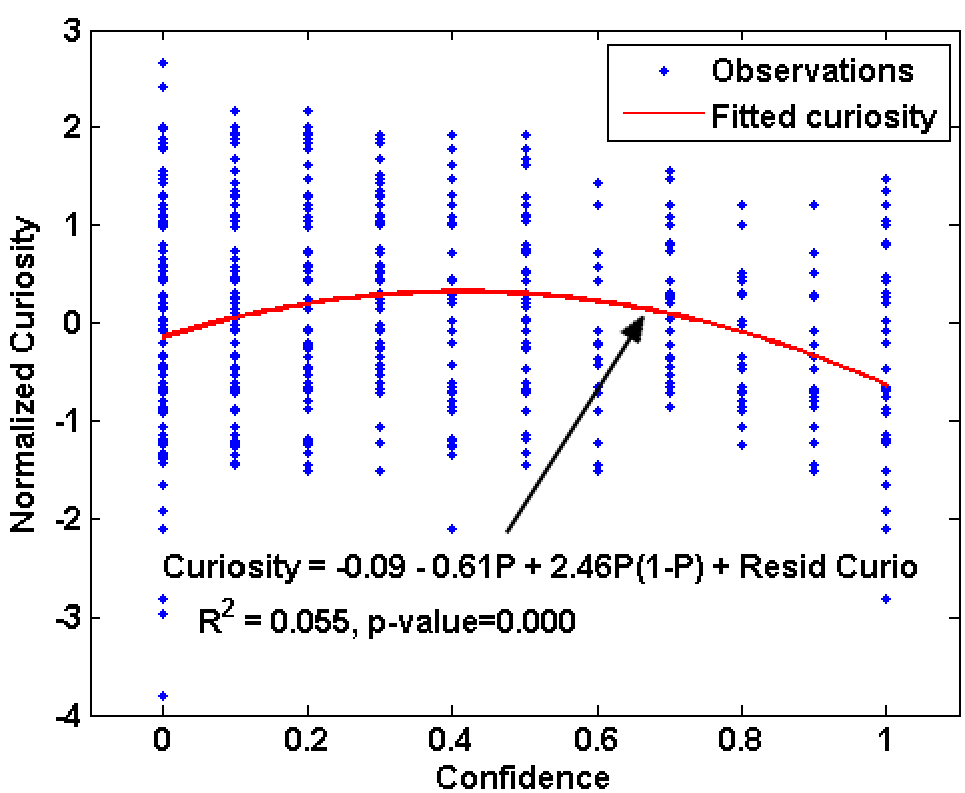

Observations
Fitted curiosity
Normalized Curiosity
Confidence
Curiosity = -0.09 - 0.61P + 2.46P(1-P) + Resid Curio
R2 = 0.055, p-value=0.000
3
2
1
0
-1
-2
-3
-4
0
0.2
0.4
0.6
0.8
1

Figure S2: Distributions of curiosity relative to confidence (P) level. X-axis: confidence rating, y-axis: subject-normalized curiosity rating. (A) Distribution of curiosity relative to confidence level for Experiment 2 (N=640). Red line indicates a fitted curiosity against P and P(1-P). Fitted curiosity shows a similar inverted U-pattern as in the fMRI study but with a peak at confidence of .29 and lower R^2. (B) Distribution of curiosity relative to confidence level for Experiment 3 (N=1400). Fitted curiosity shows a similar inverted U-pattern as in the previous studies and with a peak at confidence of .38.

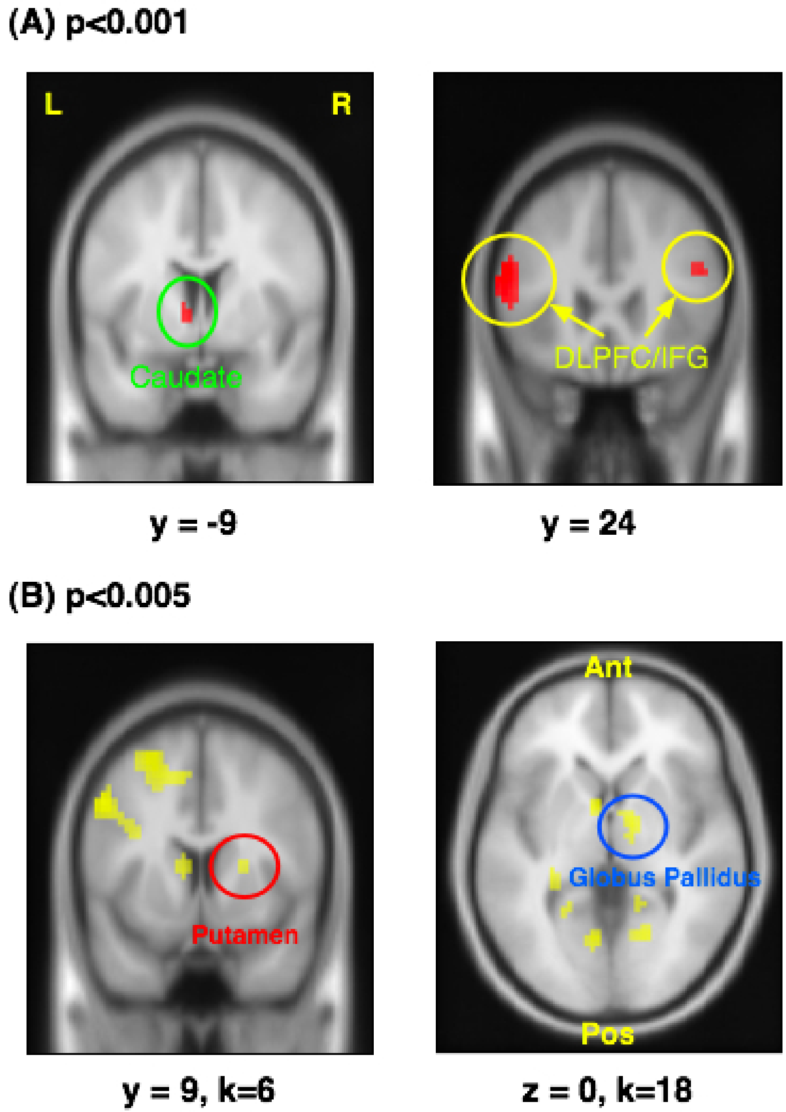
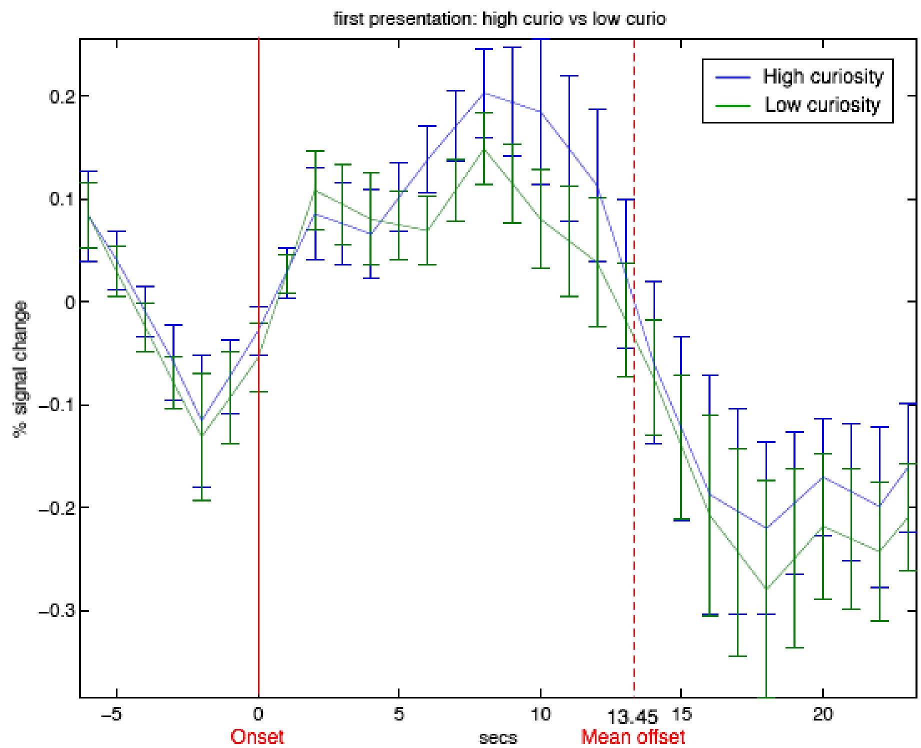


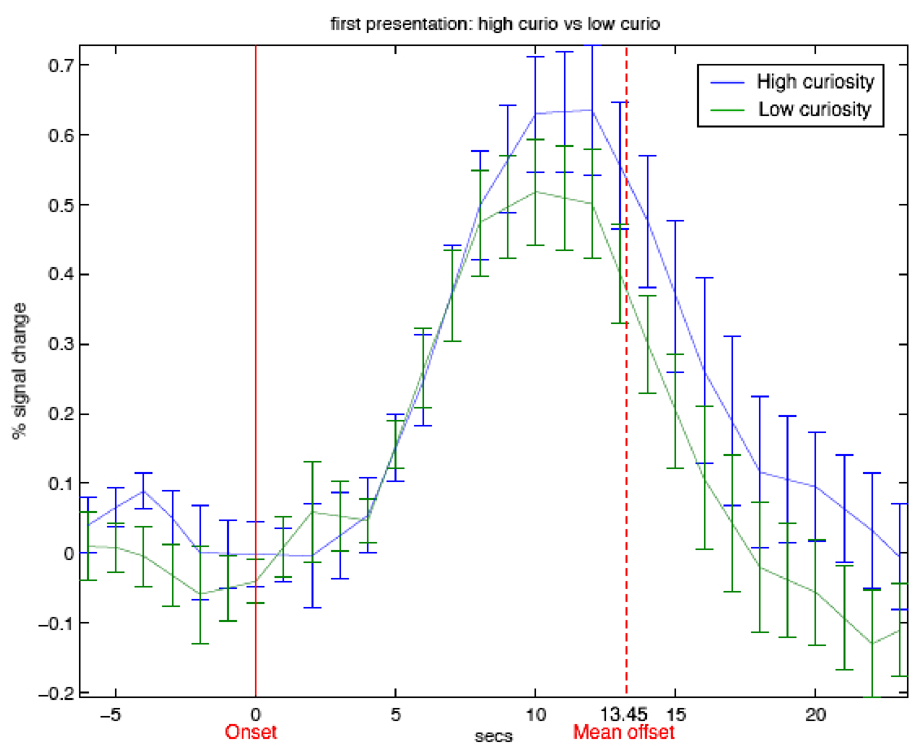
Figure S3: First question presentation contrast (High > Low) using curiosity median split. (A) At uncorrected p<0.001, extent threshold k>5. (*Left*) Left caudate, peak voxel: [-9,3,3], k=10. (*Right*) Left DLPFC, peak voxel: [-54, 24, 21]. (B) Activations are significant at p<0.005. These show reward-related regions which are not significant at p<.001 and hence omitted from text Fig. 1B.

(A)



first presentation: high curio vs low curio
High curiosity
Low curiosity
% signal change
0.2
0.1
0
−0.1
−0.2
−0.3
−5
0
5
10
13.45
15
20
Onset
secs
Mean offset

(B)



first presentation: high curio vs low curio
High curiosity
Low curiosity
% signal change
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−5
0
5
10
13.45
15
20
Onset
secs
Mean offset

Figure S4: Hemodynamic responses (HDR) in the caudate (A) and left PFC (B) separated by curiosity (High versus Low) during the first presentation in the curiosity median split analysis. A question was presented for 12~15 seconds during the first presentation (the mean presentation time, or the offset relative to onset, is 13.45 sec). Both questions significantly activate the caudate, but high-curiosity responses are persistently more activating. Second-by-second differences are generally significant, but analyses which cumulate activation across the entire presentation epoch are highly significant (see text). (A) HDR of the peak voxel ([x, y, z] = [-9, 3, 3]) of the cluster in Fig. S4A *left*. (B) HDR of the peak voxel ([-54, 24, 21]) of the cluster (yellow circle) in Fig. S4A *right*.

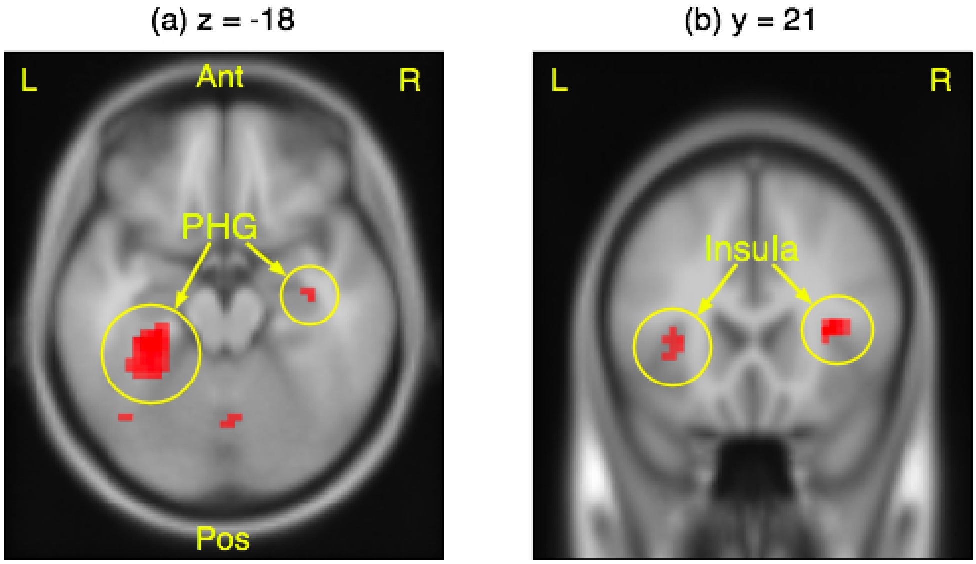
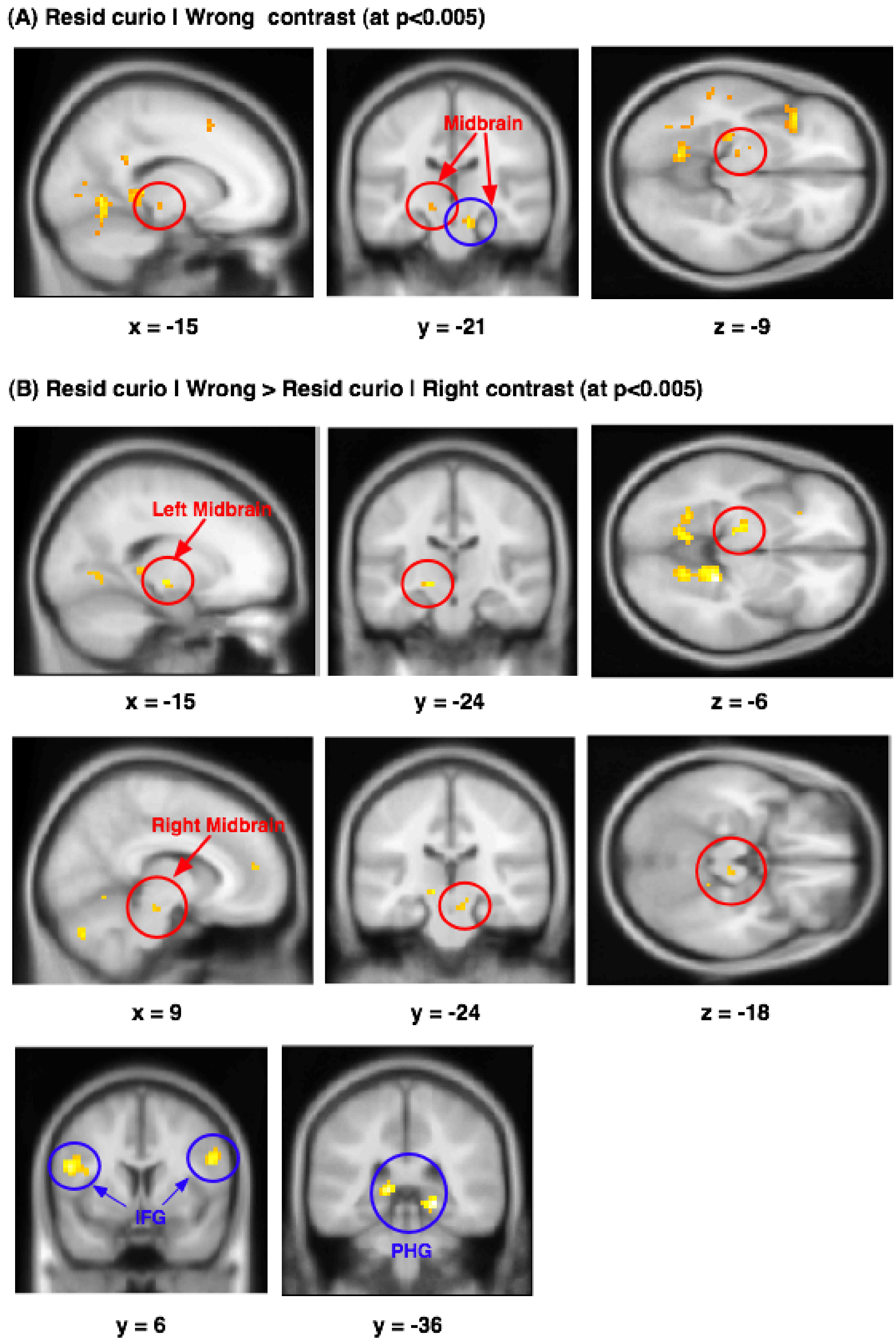


Figure S5. Neural correlates of uncertainty (*P(1-P)*) in the first and second question presentations. (A) First presentation: Parahippocampal gyri activation in *P(1-P)* contrast from the residual curiosity model. (B) Second presentation: Bilateral insula activation in the *P(1-P)* contrast from residual curiosity model ($p<0.005$).



(A) Resid curio I Wrong contrast (at p<0.005)
Midbrain
x = -15
y = -21
z = -9
(B) Resid curio I Wrong > Resid curio I Right contrast (at p<0.005)
Left Midbrain
x = -15
y = -24
z = -6
Right Midbrain
x = 9
y = -24
z = -18
IFG
PHG
y = 6
y = -36

(C)

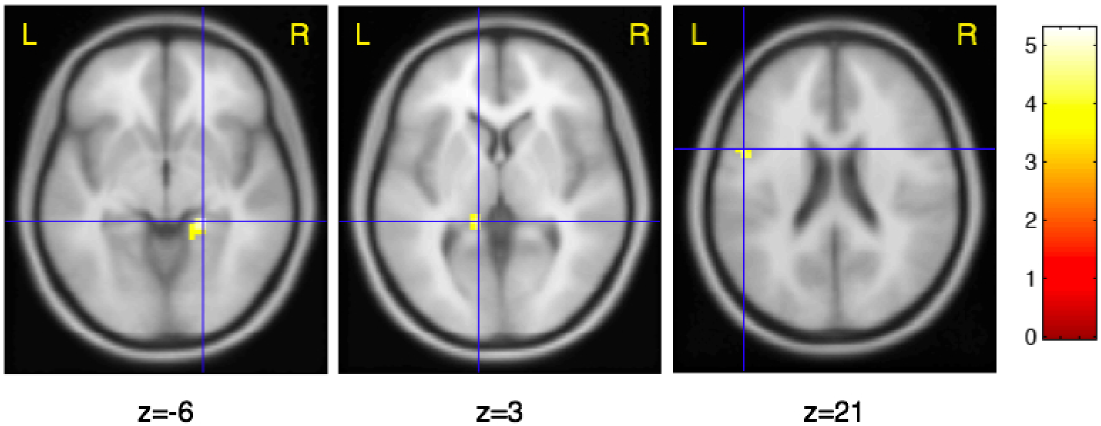


Figure S6: Effect of curiosity modulated by correctness of guess. Residual curiosity analysis in the answer display epoch. Uncorrected, $p<0.005$, extent threshold >5 voxels. (A) The brain areas that correlate with the residual curiosity when a guess was wrong. (B) Left midbrain: *x*,*y*,*z*=-18,-18,-6. Right midbrain: *x*,*y*,*z*=9,-24,-18. Left IFG: *x*,*y*,*z*= -51,6,21. Right IFG: *x*,*y*,*z*=51,6,24. Left PHG: *x*,*y*,*z*=-12,-36,3. Right PHG: *x*,*y*,*z*=21,-36,-6. (C) Residual curio|wrong > Residual curio|right contrast at $p<0.001$ (uncorrected). Bilateral PHG (left, middle), left IFG (right).

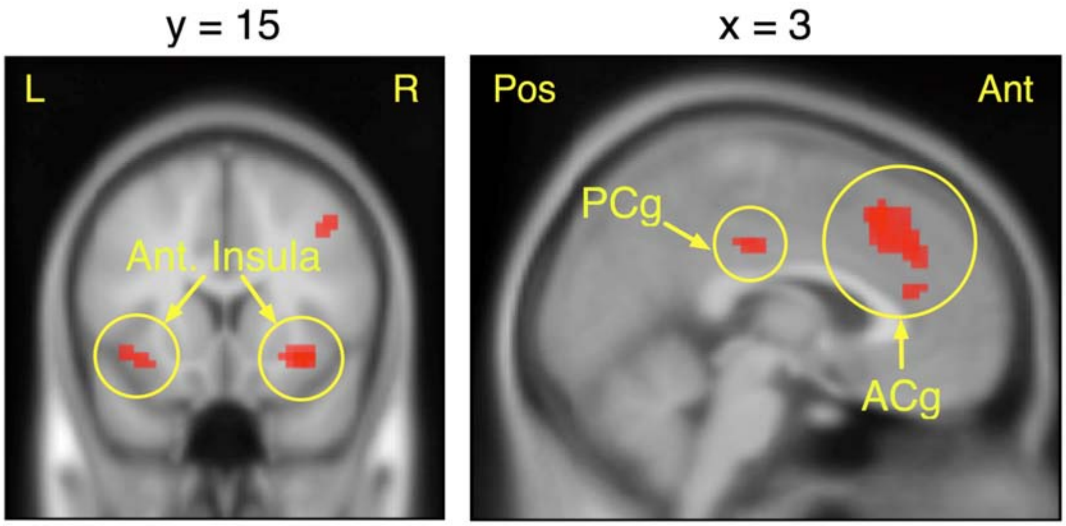


Figure S7. Regions with activity correlated with negative surprise (wrong answers × confidence P) during answer revelation. Bilateral anterior Insula (BA13) (right: *x*,*y*,*z*=-36,15,-9, *t*(18)=4.3; left: *x*,*y*,*z*=33,15,-9, *t*(18)=5.92), ACg (BA 32/9) (*x*,*y*,*z*=9,33,15, *t*(18)=4.37) and PCg (*x*,*y*,*z*=0,-24,36, *t*(18)=5.02).

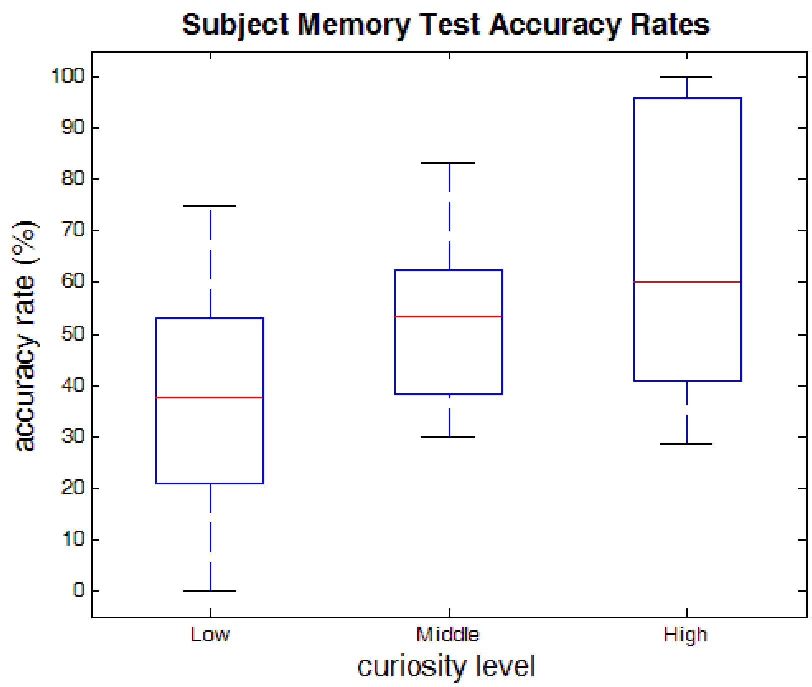


Figure S8: Memory Test Accuracy Rates (N=13; the participants who returned in 3 weeks was included.) Box plots of recall accuracy rates. Questions are sorted into three curiosity-level terciles for each subject separately.

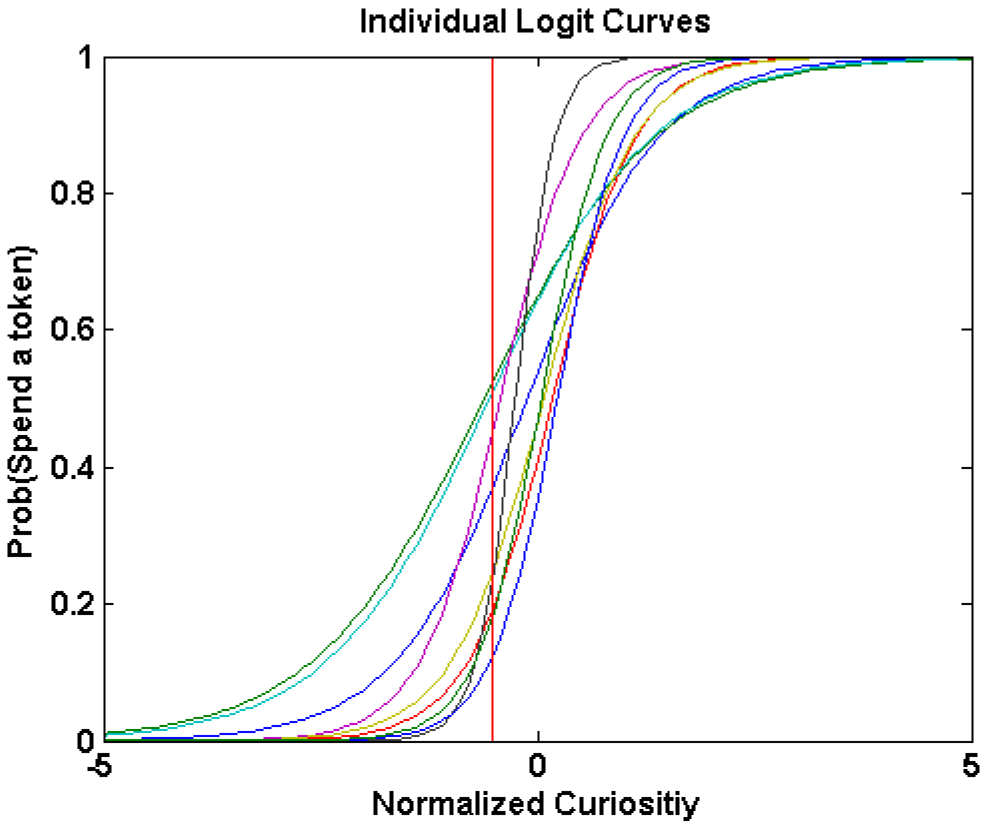


Figure S9: Individual logit curves of the token group. Token-spending behavior depends on levels of curiosity. This pattern does not change when *P* and *P(1-P)* are also included in the model.

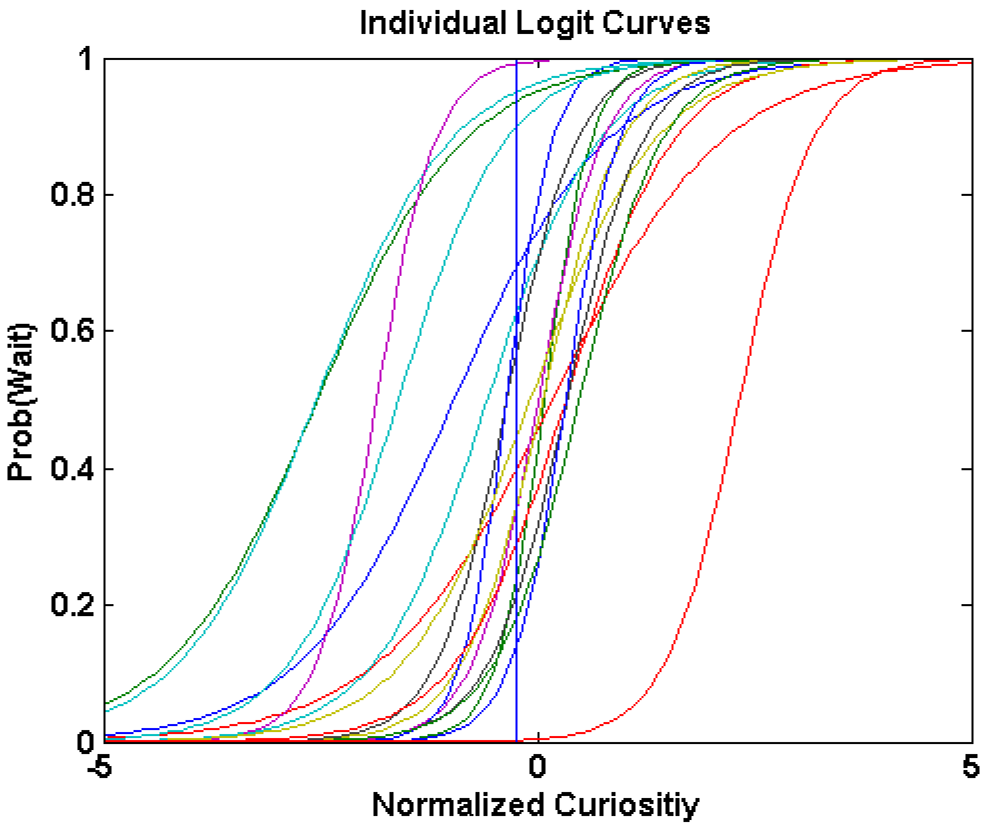


Figure S10: Individual logit curves of the waiting time group. The decision to wait depends on curiosity level. For most of the subjects, this does not change when *P* and *P(1-P)* are also included in the model.

SUPPORTING TABLES

Table S1: Distributions of curiosity relative to confidence (P) level. Most subjects show a quadratic relationship between curiosity and confidence level at an individual level. The table includes results from regressing fitted curiosity against constant, P, and P(1-P) and the confidence level which has the maximum curiosity (based on the regression estimates). Note that 12 of 19 subjects have estimated probabilities with maximum curiosity between .40 and .60.

Subject ID	Coefficients			R^2	*P with maximum curiosity*
	Intercept	*P*	*P(1-P)*		
1	-0.06	-1.51	4.00	0.19*	0.32
2	-0.4	-0.32	4.16	0.13	0.47
3	-0.17	-0.39	2.47	0.08	0.43
4	0.26	-1.38	3.18	0.33***	0.29
5	-0.88	0.33	4.77	0.19**	0.54
6	-0.49	-0.41	5.24	0.30**	0.47
7	-0.21	-1.20	6.40	0.56***	0.42
8	0.38	-1.68	2.51	0.49***	0.17
9	-1.73	0.74	8.25	0.44***	0.55
10	-0.61	0.86	1.71	0.12	0.76
11	-0.77	0.87	2.07	0.11	0.72
12	-1.58	-0.02	9.86	0.53***	0.51
13	0.1	-1.60	6.11	0.66***	0.38
14	-1.14	-0.12	7.84	0.69***	0.50
15	-0.43	-0.34	4.16	0.13	0.47
16	-0.48	0.07	3.68	0.13	0.52
17	-2.16	0.77	9.89	0.68***	0.55
18	-0.92	1.07	2.40	0.12	0.73
19	-0.85	-0.67	8.37	0.54***	0.47

Note: Confidence ratings (0% ~ 100%) are rescaled to range from 0 to 1.
*: significant at $p<0.05$.
**: $p<0.01$.
***: $p<0.001$.

Table S2: Descriptive statistics for Behavioral Data

(A) Statistics for binned curiosity (n=740)

Confidence	0	0.1	0.2	0.3	0.4	0.5
Mean	-0.42	-0.01	0.14	0.13	0.51	0.32
St. dev	1.16	1.09	0.84	0.85	0.73	0.74
Variance	1.34	1.19	0.71	0.73	0.54	0.55

Confidence	0.6	0.7	0.8	0.9	1	TOT
Mean	0.56	0.40	0.23	-0.38	-1.08	0.62
St. dev	0.61	0.72	0.67	0.84	0.92	0.56
Variance	0.37	0.52	0.45	0.70	0.84	0.31

(B) Global (Total) statistics*

Total	Confidence (n=716)	Curiosity (n=740)
Mean	0.48	0.00
St. Dev	0.33	0.99
Variance	0.11	0.98

Correlation	P	P(1-P)
Curiosity	-0.13***	0.44***
P	1	0.00
P(1-P)	0.00	1

Note: Curiosity is individually normalized by subtracting the subject-specific mean and dividing by subject-specific standard deviation (so normalized ratings have a mean of 0 and a standard deviation and variance of 1).
P : Confidence rating (scaled down to 0-1 scale)
* TOT (Tip of the tongue, not numerical) responses excluded (the number of TOT responses is 24) from calculating the statistics for confidence rating.
*** significant at $p < 0.0005$

Table S3: Two-sample t-test of accuracy of fMRI subjects' post-scan answers and Experiment 2 subjects' online answers. Equal variances assumed. One outlier is excluded from the follow-up subject group. The outlier subject (ID 8) was a foreign student who visited Caltech for the summer and showed strong outlying underperformance (accuracy rate = 0.075). The fMRI-behavioral group difference is slightly larger (.31 vs. .26) and slightly more significant if the outlier is included.

	fMRI subjects	*Experiment 2 Behavioral subjects*
Mean	0.31	0.27
Variance	0.01	0.01
Observations	19	15
Pooled Variance	0.01	
p-value (two-tailed)	.11	

Table S4: Pupil dilation response (PDR) regressions. Regress average PDR (individual mean=100) with curiosity level (CURIO), controlling for individual fixed effects (results not shown) and a quadratic time (QUESTION) trend; standard errors in parentheses. N<640 since some PDR are missing (blinks, etc.)

Period of Interest	Anticipation (-1~0secs)	Answer viewing (0~1secs)	Drop-off (1~2secs)
Constant	106.741*** (1.745)	107.941*** (1.721)	102.200*** (1.607)
curiosity C	0.740* (0.358)	0.738* (0.354)	0.384 (0.329)
confidence P	0.089* (0.036)	0.254*** (0.036)	0.247*** (0.033)
uncertainty P*(1-P)	0.0008* (0.0004)	0.0024*** (0.0004)	0.0027*** (0.0004)
QUESTION	-0.398*** (0.120)	-0.433*** (0.118)	-0.392*** (0.110)
$QUESTION^2$	0.006* (0.003)	0.006* (0.003)	0.005 (0.003)
N	632	639	636
F	6.79	9.809	9.476
F-test p-value	0	0	0
R^2	0.155	0.216	0.211

Note: t-Test p-values lower than *5 percent, ** 1 percent, and *** 0.1 percent. QUESTION denotes the number in which the question appeared in the temporal order to capture adaptation effects. Note that curiosity reliably increases PDR just before and after viewing the answer (second and third column results) but is insignificant in the 1-2 seconds after the answer presentation, while the effects of confidence and uncertainty persist.

Table S5: Memory Test Regressions. Predict correct recall (1=recalled the correct answer in memory test, 0=otherwise) with confidence (*P*), uncertainty (*P(1-P)*), correct or not initially (INI-CORRECT), and curiosity level interacting with correct or not initially (CURIO*INI-CORRECT, CURIO*INI-WRONG, respectively), controlling for individual fixed effects (fixed effect results not shown).

Regression Method	OLS (s. e.)	OLS (s. e.)	OLS (s. e.)	Logit (s. e.)	Logit (s. e.)
Constant (Last subject)	0.362*** (0.075)	0.362*** (0.075)	0.386*** (0.070)	-0.788* (0.371)	-0.752* (0.375)
CONFIDENCE (P)	0.474*** (0.072)	0.478*** (0.087)	0.127 (0.091)	2.686*** (0.444)	3.142*** (0.676)
UNCERTAINTY (P*(I-P))	-	-0.017 (0.257)	-0.083 (0.240)	-	-1.573 (1.624)
INI-CORRECT (a)	-	-	0.452*** (0.052)	-	-
CURIO*INI-CORRECT	0.033 (0.040)	0.034 (0.042)	0.035 (0.039)	0.104 (0.232)	0.166 (0.247)
CURIO*INI-WRONG	0.072** (0.024)	0.072** (0.024)	0.078*** (0.022)	0.345** (0.120)	0.350** (0.120)
N	520	520	520	520	520
F–statistic/ LR	6.952	6.505	11.540	99.763	100.735
F-statistic/LR-test p-value	0.000	0.000	0.000	0.000	0.000
R^2	0.147	0.145	0.257	0.187	0.189

Note: t-Test p-values lower than *5 percent, ** 1 percent, and *** 0.1 percent.
(a) Logit analysis including initial correctness could not be performed due to multicollinearity.

Table S6: Group logistic regression of curiosity on decision to spend a token. The dependent variable, decision to spend a token, was regressed on the normalized curiosity and a constant. The dependent variable was coded as 1 if a subject spent a point and 0 otherwise.

Random-effects logistic regression		# of obs.	400
Group variable: subject		# of groups	10
Random effects U_i ~ Gaussian		Obs./group	40
		Wald chi2(1)	120.15
Log likelihood	-172.61	Prob>chi2	0

Prob(spend a point)	Coefficient	S.E.	z	P>|z|	95% Confidence Interval	
normalized curiosity	1.96	0.18	10.96	0.000	1.61	2.31
constant	0.21	0.14	1.56	0.12	-0.05	0.48
/lnsig2u	-14	.			.	.
sigma_u	0.00	.			.	.
rho	2.53E-07	.			.	.

Likelihood-ratio test of rho = 0: chibar2(01) = 0.00, Prob>= chibar2 = 1.00

Table S7: Group logistic regression of curiosity on decision to wait for an answer. The dependent variable, decision to wait for the answer, was regressed on the normalized curiosity and a constant. The dependent variable was coded as 1 if a subject waited and 0 otherwise.

Random-effects logistic regression		# of obs.	1000
Group variable: subject		# of groups	20
Random effects U_i ~ Gaussian		Obs./group	50
		Wald chi2(1)	209.3
Log likelihood	-377.91	Prob>chi2	0

Prob(wait)	Coefficient	S.E.	z	P>|z|	95% Confidence Interval	
normalized curiosity	1.88	0.13	14.47	0.000	1.63	2.14
constant	0.31	0.16	1.89	0.06	-0.01	0.63
/lnsig2u	1.34	0.29			0.78	1.91
sigma_u	1.96	0.28			1.47	2.60
rho	0.54	0.07			0.40	0.67

Likelihood-ratio test of rho = 0: chibar2(01) =325.07, Prob>= chibar2 = 0

Table S8: Summary of individual logistic regression of the normalized curiosity on decision to spend cost. The coefficient for an implicit constant term is not reported here.

(a) Token condition

Subject ID	Coeff. for norm. curiosity	z-stat	*p*-value	pseudo-R^2
1	1.33	3.14	0.002	0.23
2	1.02	2.55	0.011	0.15
3	2.09	3.19	0.001	0.36
4	1.08	2.57	0.010	0.16
5	2.18	3.86	0.001	0.49
6	1.92	2.86	0.004	0.31
7	4.42	2.61	0.009	0.72
8	2.64	3.27	0.001	0.47
9	2.69	3.52	0.001	0.54

Note:(1) The coefficient for an implicit constant term is not reported here.
(2) For subject 10, the normalized curiosity level of -.524 predicts data perfectly—that is, the probability of waiting jumps at -.524 from 0 to 1.

(b) Time condition

Subject ID	Coeff. for norm. curiosity	z-stat	*p*-value	pseudo-R^2
1	1.13	2.97	0.003	0.18
2	3.70	3.26	0.001	0.63
3	1.01	2.78	0.005	0.14
4	1.55	3.54	0.000	0.28
5	2.69	3.88	0.000	0.52
6	1.46	3.19	0.001	0.23
7	2.49	3.79	0.000	0.47
8	3.81	3.55	0.000	0.70
9	1.17	1.75	0.08	0.14
10	1.60	3.81	0.000	0.31
11	1.28	2.74	0.006	0.36
12	2.90	1.41	0.158	0.26
13	1.39	3.66	0.000	0.26
14	2.27	3.69	0.000	0.43
15	3.24	3.29	0.001	0.56
16	2.08	3.76	0.000	0.42
17	2.36	1.92	0.055	0.44
18	1.61	2.88	0.004	0.33

Note: (1) For subject 19, the normalized curiosity level of -.232 predicts data perfectly—that is, the probability of waiting jumps at -.232 from 0 to 1.
(2) For subject 20, the normalized curiosity level of -1.921 predicts data perfectly.

Table S9: Summary of individual likelihood-ratio tests. The coefficient for an implicit constant term is not reported here.

(a) Token condition

	Likelihood		
Subject	Unrestricted Model	Restricted Model	*p*-value
1	-20.20	-21.20	0.366
2	-22.01	-22.50	0.609
3	-16.35	-17.49	0.323
4	-21.89	-22.18	0.748
5	-12.85	-13.44	0.556
6	-18.43	-18.94	0.598
7	-7.32	-7.87	0.575
8	-13.47	-14.42	0.387
9	-10.72	-12.86	0.117

Note: For subject 10, the normalized curiosity level (the restricted model) predicts data perfectly.

(b) Time condition

	Likelihood		
Subject	Unrestricted Model	Restricted Model	*p*-value
1	-23.31	-25.05	0.175
2	-10.43	-12.15	0.179
3	-27.69	-29.58	0.150
4	-15.92	-23.59	0.001
5	-16.24	-16.35	0.636
6	-24.43	-26.65	0.108
7	-17.95	-17.95	0.999
8	-9.57	-10.05	0.620
10	-20.93	-23.40	0.085
11	-8.23	-8.95	0.485
13	-13.63	-25.77	0.000
14	-13.67	-18.96	0.005
15	-13.64	-14.95	0.270
16	-14.65	-18.71	0.017
17	-4.28	-4.73	0.642
18	-8.67	-13.54	0.008

Note: (1) For subject 5, the unrestricted model only includes the normalized curiosity and confidence P as independent variables due to colinearity.
(2) For subject 9 and 12, confidence P predicts data perfectly.
(3) For subject 19 and 20, the normalized curiosity predicts data perfectly.

Table S10~S12: Coordinates of voxels

All locations are reported in MNI coordinates.
Uncorrected p<0.001, extent threshold k=5 voxels unless noted.
Voxel size: [3.0, 3.0, 3.0] mm

Table S10: Brain regions associated with high curiosity vs low curiosity (curiosity median split analysis)

(A) First presentation: (1^{st} H>1^{st} L)

Region	L/R	MNI coordinates x	y	z	Spatial Extent (voxels)	t statistic
Caudate Head	L	-9	3	3	10	4.04
Inferior Frontal Gyrus/BA45	L	-54	24	21	112	5.71
Inferior Frontal Gyrus	R	48	24	21	5	4.01
Parahippocampal Gyrus	L	-33	-39	-12	21	4.04
Parahippocampal Gyrus	R	36	-30	-18	5	4.46
Medial Frontal Gyrus	L	-12	36	48	26	4.49
MFG, Pre-motor Cortex	L	-27	15	57	70	5.71
Lingual gyrus	R	18	-63	-3	11	4.57
Cerebellum	R	36	-69	-36	34	4.67

(B) Second presentation: (2^{nd} H>2^{nd} L)

Region	L/R	MNI x	Y	z	Spatial Extent (voxels)	t statistic
Inferior Frontal Gyrus	L	-48	30	21	24	4.99

Table S11: Brain regions linearly associated with residual curiosity (Residual curiosity analysis)

(A) Answer epoch: Resid curio|Wrong

Region	L/R	MNI x	y	z	Spatial Extent (voxels)	T statistic
Parahippocampal Gyrus	L	-24	-27	-6	19	4.69
Inferior Frontal Gyrus	L	-54	9	24	76	4.48
DLPFC/BA 9	L	-51	15	30		4.23
Inferior Frontal Gyrus	L	-45	30	3	88	5.98
Lingual Gyrus	L	-12	-63	-6	40	5.31
Superior Temporal Gyrus	L	-60	-57	12	5	4.6
Superior Frontal Gyrus	L	-21	48	12	9	4.36
Medial Frontal Gyrus	L	-6	15	51	8	4.07
Cerebellum	R	9	-72	-30	125	6.12

(B) Answer epoch: Resid curio|Wrong - Resid curio|Right

Region	L/R	MNI x	MNI y	MNI z	Spatial Extent (voxels)	t statistic
Parahippocampal Gyrus	R	21	-36	-6	18	5.28
Parahippocampal Gyrus	L	-12	-36	3	8	4.67
Inferior Frontal Gyrus	L	-51	6	21	12	4.56

Table S12: Brain regions linearly associated with uncertainty P(1-P) (Residual curiosity analysis)

(A) First presentation

Region	L/R	MNI x	MNI y	MNI z	Spatial Extent (voxels)	t statistic
Parahippocampal Gyrus	L	-30	-33	-18	124	6.33
Posterior Cingulate	L	-9	-48	6	128	5.24
Posterior Cingulate	R	12	-48	6	16	4.3
Middle Frontal Gyrus	L	-30	51	12	6	5.14
Lateral Ventricle	R	36	-12	-21	15	4.73
Cerebellum	R	36	-63	-36	167	5.31
Declive	R	15	-69	-21	28	4.23
Declive	L	-42	-66	-21	5	3.97

Note: The left caudate head ([-6,3,3], k=6) is detected at $p<0.005$.

(B) Second presentation

Region	L/R	MNI x	MNI y	MNI z	Spatial Extent (voxels)	t statistic
Insula	R	30	21	9	13	5.61

SUPPORTING MATERIALS

Questions, answers, and average curiosity ratings

The order of presentation of questions was randomized within run.

Question **(Answer, Average curiosity rating across subject)**
Run 1
What rock and roll band performs "I want to Rock and Roll All Night"? (Kiss, 3.84)
What unfortunate handicap did Thomas Edison suffer from? (Deafness, 4.63)
What city was "Groundhog Day", starring Bill Murray, filmed in? (Pittsburgh, 3.53)
What book is the most shoplifted book in the world? (The Bible, 5.05)
What is the museum-surrounded space in Washington DC called? (The Mall, 3.89)
How long were Jerry Seinfeld and his pals sentenced in the series finale? (One year, 2.37)
What is the only type of animal besides a human that can get a sunburn? (Pig, 5.42)
Which school has the most students over age 25 according to US News? (University of Phoenix, 3.74)
What snack food is an ingredient in the explosive dynamite? (Peanuts, 5.63)
What is the most sober school according to The Princeton Review? (Brigham Young University, 5.10)
Run 2
What city is referred to as "Pittsburgh of the South"? (Birmingham, AL, 3.83)
What invention should make Ts'ai Lun, a 2nd century inventor, a household name? (Paper, 5)
What breed of dog is the only animal whose evidence is admissible in American courts? (Bloodhound, 4.94)
What animal can shed up to 30,000 teeth in its lifetime? (Shark, 4.33)
Who was the first host of the comedy show Saturday Night Live? (George Carlin, 3.5)
What is the only country in the world where women dominate the government? * (Belgium, 5.89)
What type of political campaign is characterized by many stops in small towns? (Whistle-stop campaign, 3.89)
What instrument was invented to sound like a human singing? (Violin, 5.72)
From what city in the United States did Coca-Cola originate? (Atlanta, GA, 3.78)

What animal's excrements are consumed as luxury food?
(Bats, 4.83)

Run 3

What everyday food will make a drug test show up positive?
(Poppy seeds, 3.61)
What industry uses 20% of China's harvested plants?
(Medicine, 4.72)
What electronic tem is stolen most often on the NYC subways? *
(iPods, 4.1111)
What famous person was Dolly the cloned sheep named after?
(Dolly Parton, 3.33)
What fictional character in Treasure Island lends its name to a fast food chain?
(Long John Silver, 4.11)
What is the name of the galaxy that Earth is a part of?
(Milky Way, 2.28)
What is the most abundant mineral in the human body?
(Calcium, 5.11)
What president has three 'A's in his first name where each has a different sound?
(Abraham Lincoln, 3.39)
What title was Catherine of Aragon known by after she divorced Henry VIII?
(Dowager Princess of Wales, 4.44)
What country has won the most Miss World beauty contests? *
(Venezuela, 3.89)

Run 4

What is the only country in the world that has a bill of rights for cows?
(India, 3.47)
What was the first animated film to win an Academy Award?
(Beauty and the Beast, 4.37)
What item on the McDonald's menu has the most calories? *
(Chicken Selects, 20 Piece, 4.84)
What city has the only drive-thru post office in the world?
(Chicago, 4.26)
What crime is punishable if attempted, but not if committed?
(Suicide, 4)
What secular philosopher's teaching influenced life in his country for 2000 years?
(Confucius, 4.63)
What Beatles song lasted the longest on the American charts?
(Hey Jude, 5)
What is the only type of lizard that has a voice?
(Gecko, 4.47)
Which sports athlete has appeared in McDonald's, Nike and Hanes advertisements?
(Michael Jordan, 2.89)
What was put in place by the Greeks before and during all the Ancient Olympic festivals?
(A truce, 4.47)

Note: The questions in asterisk (*) are updated or replaced by the following set:

What male body part did Mademoiselle magazine find to be	Eyes

the favorite of most women?	
What part of a woman's body were ancient Chinese artists forbidden to paint?	Her foot
What creature proved to be much faster than a horse in a 1927 race in Sydney, Australia?	The Kangaroo
What item on the McDonald's menu has the most calories?	Chocolate Triple Thick Shake (32 fl oz cup), 1160 kcal

Additional Questions and answers used in Experiment 3.

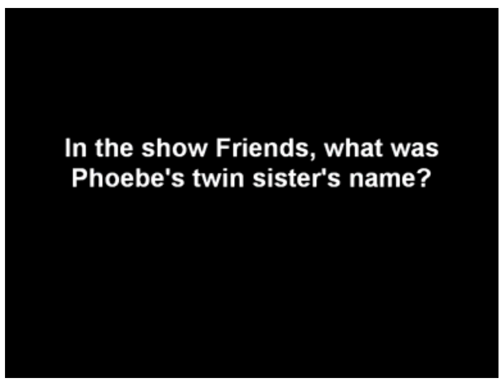
Questions	Answer
What did the girls in medieval Spain put in their mouths to avoid unwanted kisses?	Toothpicks
What drupaceous fruit were Hawaiian women once forbidden by law to eat?	The coconut
In parts of India, the oldest brother must marry first. If he cannot find a wife, what can he choose to marry?	A tree
How many years are in an eon (aeon)?	100 million
What fat substitute got FDA approval for use in snack foods, despite reports of diarrhea and cramps?	Olestra
What organ is found only in vertebrates (animals with a backbone)?	Liver
In 1875, who helped Daniel Peter invent "milk" chocolate?	Henry Nestle
What butterfly-shaped gland is located just in front of the windpipe?	The Thyroid
What is a shark's skeleton made of?	Cartilage
Who was the first Christian emperor of Rome?	Constantine the Great

Instructions (for Experiment 1)

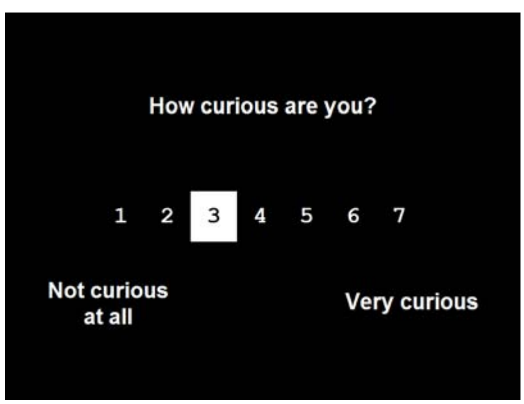
Thank you for participating in this study on curiosity. During the experiment you will be asked a series of different trivia-type questions about things that you may or may not find yourself curious about. After presenting each question, we will ask you to rate (1) how curious you are to know the answer, and (2) how confident you are that you know the answer. The answer to the question will be revealed before you move on to the next question.

The questions are presented in a pre-programmed pace. So please wait for the next rating slide after you complete the task in the question slide. You will be given only 12 to15 seconds to read each question. No matter how quickly you figure out the answer, the program will not let you continue until the full 12 to 15 seconds are up. The program will automatically move on to the next step when 12 to 15 seconds are over. Please respond quickly, but please do not speak/ think aloud.

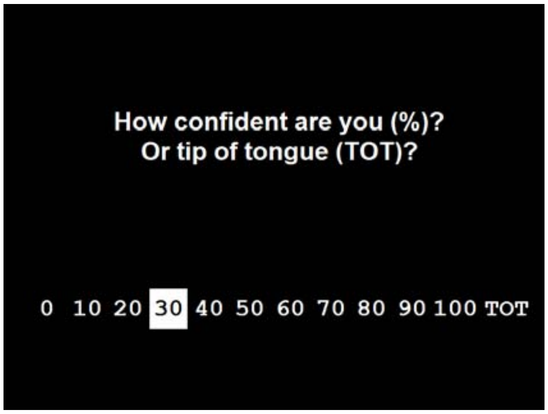
Here is the sample of a question.



After a question is presented, a screen with a sliding scale from 1 (not at all curious) through 7 (very curious) will appear (see below for the sample). Select the number that represents how curious you are about the answer. When rating curiosity, use the right (1) and left (3) buttons to scroll along the response scale. To confirm your choice, press the top (4) button.

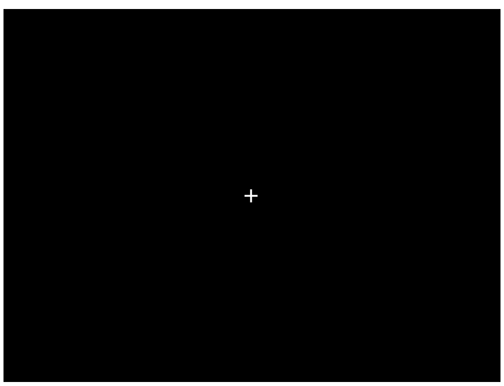


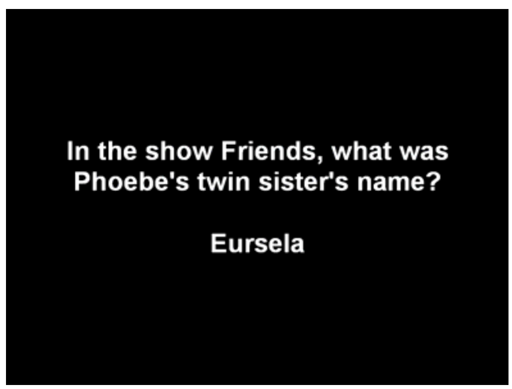
After making your selection, you will be asked to rate how confident you are of the answer or whether the answer is on the tip of the tongue (see below for the sample screen). You may respond with a sliding scale from 0% (not at all confident) through 100% (very confident) or the tip-of-the-tongue (TOT) option. The 'tip-of-the-tongue' response indicates that you feel that you know the correct answer, even though you cannot remember the exact word that corresponds with the answer at the moment. If you feel that the correct answer is on the tip-of-your-tongue, please select "TOT" response. Before selecting your option, please silently say the word to see if you actually produce it. You may use the 1 (right) and 3 (left) buttons to scroll along the response scale. The rating steps are self-paced, so the program will not move on to the next step until you press the 4 (top) button to confirm your selection.



The fixation screen will appear between and after the rating slides and then the answer slide will follow.

Here are the fixation screen (left) and the answer slide (right).





Before you move on to the next question, the fixation screen will appear again.

Before the experiment starts, you will be presented with 3 practice questions. After you answer and rate them, we will ask if you have any question. At the end of the experiment, you will be asked to debrief whether your guess was right or not and to fill out a short questionnaire. You will be paid $20 for participating in this experiment. The information we obtain from the experiment will not be used for other commercial or non-academic purposes.

Post Debriefing Sheet (for Experiment 1)

The followings are the questions we have asked you during the experiment. They are not in the same order as they were in the experiment. Please report your initial guesses in the "Your Guesses" column. If you made more than one guess, report all of them. If the answer was on the tip of the tongue and you responded with "TOT" option, please write "TOT". If you had no idea, then simply write a question mark ("?"). There is no penalty for the wrong guesses. This report is important for our study, so please report honestly. Also, if you can recall your feeling, please let us know how you felt (for example, disappointed or surprised), when the answer was revealed.

Questions	Your Guesses	Your Feeling
Which school has the most students over age 25 according to US News?		
What city was "Groundhog Day", starring Bill Murray, filmed in?		
What rock and roll band performs "I want to Rock and Roll All Night"?		
What unfortunate handicap did Thomas Edison suffer from?		
What book is the most shoplifted book in the world?		
What is the only type of animal besides a human that can get a sunburn?		
What is the most sober school according to The Princeton Review?		
How long were Jerry Seinfeld and his pals sentenced in the series finale?		
What snack food is an ingredient in dynamite?		
How is the museum-surrounded space in Washington DC referred to?		
What type of political campaign is characterized by many stops in small towns?		
What city is referred to as "Pittsburgh of the South"?		
Who was the first host of the comedy show Saturday Night Live?		
What is the only country in the world where women dominate the government?		
What animal can shed up to 30,000 teeth in its lifetime?		
What invention should make Ts'ai Lun, a 2nd century inventor, a household name?		

What breed of dog is the only animal whose evidence is admissible in American courts?

What instrument was invented to sound like a human singing?

From what city in the United States did Coca-Cola originate?

What animal's excrements are consumed as luxury food?

What title was Catherine of Aragon known by after she divorced Henry VIII?

What is the most abundant mineral in the human body?

What is the name of the galaxy that Earth is a part of?

What industry uses 20% of China's harvested plants?

What country has won the most Miss World beauty contests?

What fictional character in Treasure Island lends its name to a fast food chain?

What president has three 'A's in his first name where each has a different sound?

What famous person was Dolly the cloned sheep named after?

What electronic item is stolen most often on the NYC subways?

What everyday food will make a drug test show up positive?

What is the only country in the world that has a bill of rights for cows?

Which sports athlete has appeared in McDonald's, Nike and Hanes advertisements?

What was the first animated film to win an Academy Award?

What crime is punishable if attempted, but not if commited?

What Beatles song lasted the longest on the American charts?

What was put in place by the Greeks before and during all the Ancient Olympic festivals?

What city has the only drive-thru post office in the world?

What is the only type of lizard that has a voice?

What secular philosopher's teaching influenced life in his country for 2000 years?

What item on the McDonald's menu has the most calories?

Post Curiosity Memory Test Instructions

Thank you for participating in the follow-up memory test to the curiosity study that you participated in two weeks ago. You will be paid $15 for participating, and might receive an additional amount of money based on your performance. During the curiosity experiment you participated in two weeks ago, you were asked to read 40 trivia questions and rate how confident you were in your guesses. During this memory test, you will be given the same 40 questions. Please try to answer the questions correctly, and provide the confidence level you have in your answer. The confidence level ranges from 0% to 100%. Please do not search for answers on the internet. You will not be paid for giving right answers, but please give us your best guess as well your correct confidence levels. There is no penalty for incorrect answers (no humiliation, either). Your honest report is important for our study. Next, please tell us whether you had the correct answer last time (two weeks ago) and provide the confidence level (0~100%) which you initially indicated last time. Please try to recall what you gave last time as accurately as possible. You will receive $0.50 per correct confidence level recollection. In short, for each trivia question, you should give four answers: Your current answer, your confidence level now, as well as your answer last time and your confidence level last time. You will only be paid $0.50 per question if the fourth answer (confidence level last time) is correct.

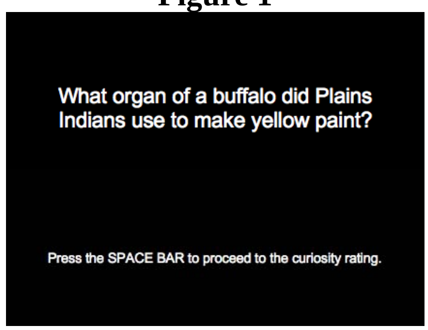
Instructions (for Experiment 3, token condition)

Thank you for participating in this study on curiosity. During the experiment you will be asked a series of different trivia-type questions about things that you may or may not find yourself curious about. After presenting each question, we will ask you to rate (1) how curious you are to know the answer, and (2) how confident you are that you know the answer. You will then be asked to type your guess about the answer to the question. Once you submit your answer, we will ask if you would like to spend a 'point' to see the answer (we will explain these points to you soon). If you spend a point, you will see the answer; if you do not spend a point, you will not see the answer. The detailed procedure will be explained below.

You will read 50 questions one at a time. There is no time limit so you can take as much time as you wish to read each question. Once you are ready to proceed, please press the SPACEBAR. Please do not speak/ think aloud.

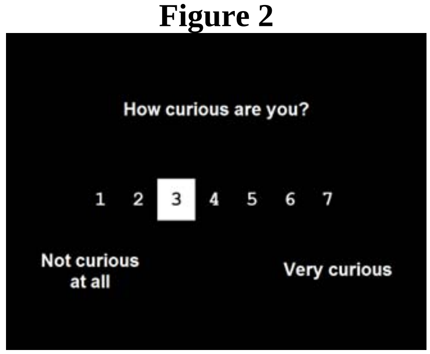
Here is a sample question:

Figure 1



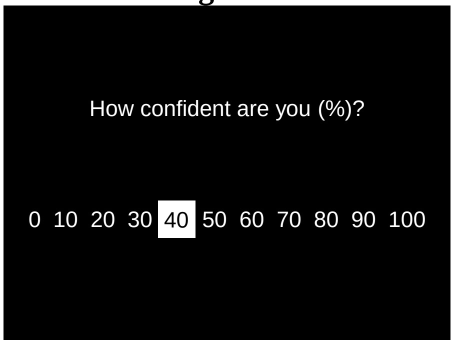
Pressing the SPACEBAR will bring the curiosity rating screen with a sliding scale from 1 (not at all curious) through 7 (very curious) (see **Figure 2** below). Select the number that represents how curious you are about the answer. When rating curiosity, use the right and left arrow keys to scroll along the response scale. To confirm your choice, press the SPACEBAR. Note that when you rate your curiosity, you should report your curiosity about the specific question presented to you, not your curiosity about the topic in general.

Figure 2



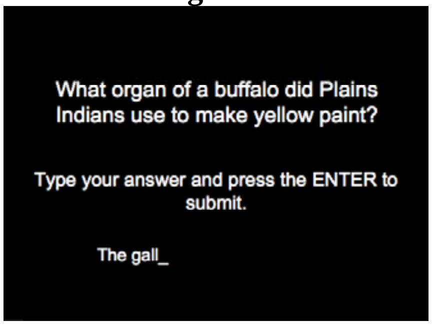
After making your selection, you will be asked to rate how confident you are that you know the answer (see **Figure 3** below). You may respond with a sliding scale from 0% (not at all confident) through 100% (very confident), in increments of 10%. You may use the right and left arrow keys to scroll along the response scale. The rating steps are self-paced, so the program will not move on to the next step until you press the SPACEBAR to confirm your selection.

Figure 3



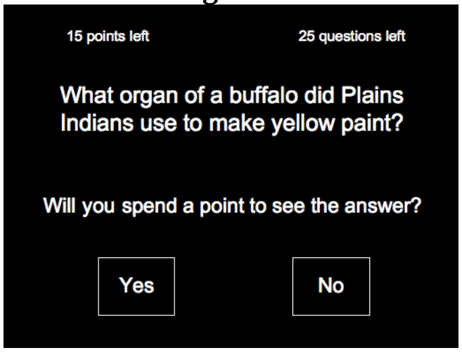
Once you complete the rating steps, we will ask you to type your answer (see **Figure 4** below). You may use the backspace to correct a typographical error. When you finish typing your answer, please press the ENTER button to submit it. There is neither penalty for wrong guesses nor prize for right guesses, so please report honestly. If you have no idea of the answer, you may type "?" as your response.

Figure 4



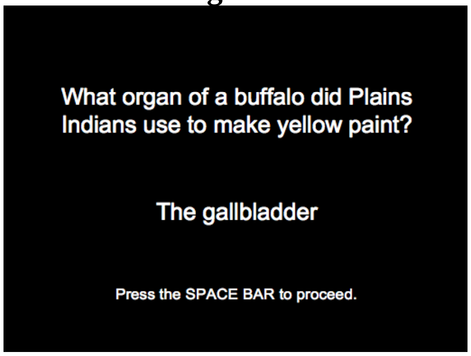
After you submit your answer, we will ask if you would like to spend a point to see the answer to the question (see **Figure 5** on the next page). You will be given **25 points** at the start and these points are yours to spend. You will need one point to see one answer. These points are **ONLY** valid during the experiment and will not be converted into cash. Note that you have only 25 points for 50 questions; that is, you cannot see all the answers – you can see only half of them. At the top of the screen, we will display the number of points you have remaining as well as the number of questions to go.

Figure 5



If you decide to spend a point to see the answer, please select "Yes" by pressing the left arrow key. Then the answer will show up in the next screen (see **Figure 6** below) and one point will be deducted from your point account. If you do not want to spend a point, please select "No" by pressing the right arrow key. This will let you skip the answer screen and move on to the next question.

Figure 6



Before the experiment starts, you will be presented with 10 practice questions. You are given 10 points for the practice questions. After you answer and rate them, we will ask if you have any questions. At the end of the experiment, you will be asked to fill out a short questionnaire. You will be paid $20 for participating in this experiment, including the show-up fee. The information we obtain from the experiment will not be used for other commercial or non-academic purposes.

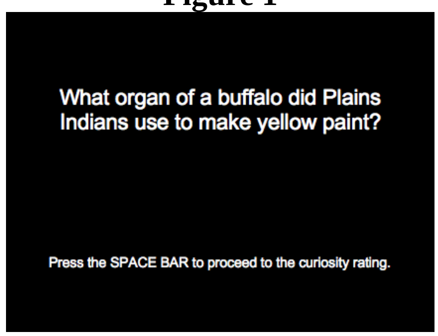
Instructions (for Experiment 3, time condition)

Thank you for participating in this study on curiosity. During the experiment you will be asked a series of different trivia-type questions about things that you may or may not find yourself curious about. After presenting each question, we will ask you to rate (1) how curious you are to know the answer, and (2) how confident you are that you know the answer. You will then be asked to type your guess about the answer to the question. Once you submit your guess, you can either wait until the actual answer shows up or skip it and move on to the next question. The detailed procedure will be explained below.

You will read 50 questions one at a time. There is no time limit so you can take as much time as you wish to read each question. Once you are ready to proceed, please press the SPACEBAR. Please do not speak/think aloud.

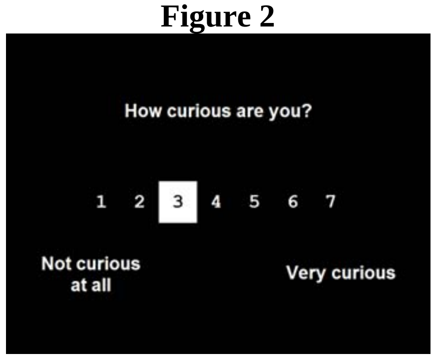
Here is a sample question:

Figure 1



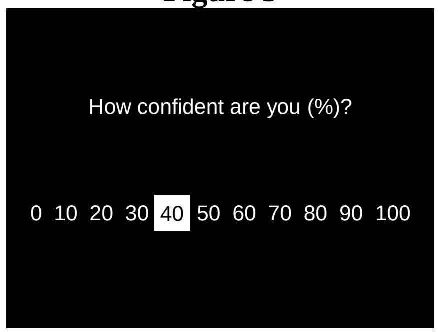
Pressing the SPACEBAR will bring up the curiosity rating screen with a sliding scale from 1 (not at all curious) through 7 (very curious) (see **Figure 2** below). Select the number that represents how curious you are about the answer. When rating curiosity, use the right and left arrow keys to scroll along the response scale. To confirm your choice, press the SPACEBAR. Note that when you rate your curiosity, you should report your curiosity about the specific question presented to you, not your curiosity about the topic in general.

Figure 2



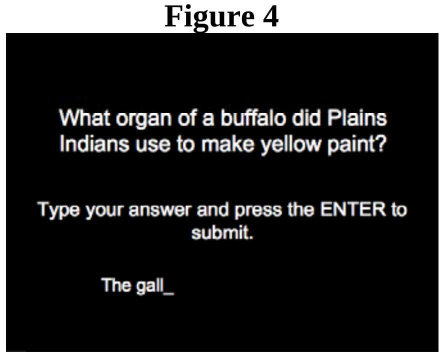
After making your selection, you will be asked to rate how confident you are that you know the answer (see **Figure 3** below). You may respond with a sliding scale from 0% (not at all confident) through 100% (very confident), in increments of 10%. You may use the right and left arrow keys to scroll along the response scale. The rating steps are self-paced, so the program will not move on to the next step until you press the SPACEBAR to confirm your selection.

Figure 3



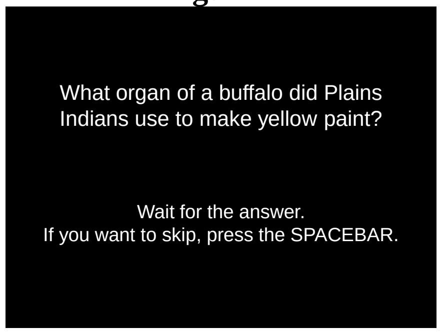
Once you complete the rating steps, we will ask you to type your answer (see **Figure 4** below). You may use the backspace to correct a typographical error. When you finish typing your answer, please press the ENTER button to submit it. There is neither a penalty for wrong guesses nor a prize for right guesses, so please report honestly. If you have no idea of the answer, you may type "?" as your response.

Figure 4



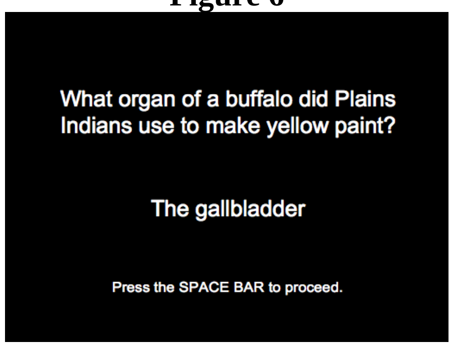
After you submit your answer, the waiting screen will appear (see **Figure 5** on the next page). You can wait for the answer if you want to see it. If you do not want to see the answer or do not want to wait, you can escape the waiting screen and proceed to the next question by pressing the SPACEBAR. Whether to wait or not is up to you. The waiting time will be at random and vary from 5 seconds to 25 seconds in each trial. To be precise, the waiting time follows a uniform distribution over 5 to 25 seconds, and hence any second over that time interval can be a waiting time. The average waiting time will be 15 seconds and the standard deviation will be 5.9 seconds. Some answers may have a shorter waiting time and others may have a longer waiting time. But you will not know in advance how long you will need to wait.

Figure 5



If you decide to wait for the answer, the answer will show up in the next screen when the allotted waiting time is up (see **Figure 6** below). Once you are ready for the next question, please press the SPACEBAR to proceed.

Figure 6



Before the experiment starts, you will be presented with 10 practice questions. After you answer and rate them, we will ask if you have any questions. At the end of the experiment, you will be asked to fill out a short questionnaire. You will be paid $20 for participating in this experiment, including the show-up fee. The information we obtain from the experiment will not be used for any commercial or non-academic purposes.

Questionnaire

1) What is your age?
2) What is your sex? (Female, Male)
3) What is your native language?
4) If English is not your native language, how fluently do you speak it?
   (not at all, somewhat, fluently, very fluently, fluently at a native speaker's level)
5) What is your occupation?
6) Are you left-handed or right-handed?
7) What is your race?
8) Have you taken any courses in Economics? If so, please list them below.
   1.
   2.
   3.
   4.
   5.

Using the scale below, please respond to each statement according to how you would normally describe yourself. Work at your own pace, but do not spend too much time deciding on your responses.

1	2	3	4	5	6	7
strongly disagree			neither agree nor disagree			strongly agree

1	I would describe myself as someone who actively seeks as much information as I can in a new situation.	1	2	3	4	5	6	7
2	When I am participating in an activity, I tend to get so involved that I lose track of time.	1	2	3	4	5	6	7
3	I frequently find myself looking for new opportunities to grow as a person (e.g., information, people, resources).	1	2	3	4	5	6	7
4	I am *not* the type of person who probes deeply into new situations or things.	1	2	3	4	5	6	7
5	When I am actively interested in something, it takes a great deal to interrupt me.	1	2	3	4	5	6	7
6	My friends would describe me as someone who is "extremely intense" when in the middle of doing something.	1	2	3	4	5	6	7
7	Everywhere I go, I am out looking for new things or experiences.	1	2	3	4	5	6	7

Any comments?