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The seductive lure of curiosity: information as a motivationally salient reward

Lily FitzGibbon[1], Johnny King L Lau[1] and Kou Murayama[1,2]

Humans are known to seek non-instrumental information, sometimes expending considerable effort or taking risks to receive it, for example, 'curiosity killed the cat'. This suggests that information is highly motivationally salient. In the current article, we first review recent empirical studies that demonstrated the strong motivational lure of curiosity – people will pay and risk electric shocks for non-instrumental information; and request information that has negative emotional consequences. Then we suggest that this seductive lure of curiosity may reflect a motivational mechanism that has been discussed in the literature of reward learning: *incentive salience*. We present behavioral and neuroscientific evidence in support of this idea and propose two areas requiring further investigation – how incentive salience for information is instigated; and individual differences in motivational vigor.

Addresses
[1] University of Reading, School of Psychology and Clinical Language Science, University of Reading, Harry Pitt Building, Reading, RG6 7BE, United Kingdom
[2] Kochi University of Technology, Research Institute, Kochi University of Technology, 185 Miyanokuchi, Tosayamada, Kami City, Kochi, 782-8502, Japan

Corresponding authors:
FitzGibbon, Lily (l.t.fitzgibbon@reading.ac.uk), Murayama, Kou (k.murayama@reading.ac.uk)

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Introduction

Humans are known to seek non-instrumental information, or become 'curious' about such information [1], such as answers to obscure trivia questions, or celebrity gossip that will have little future value. People's curiosity for non-instrumental information is also illustrated in the fact that people will pay or exert effort to access information. For example, one might pay for a subscription to a gossip magazine or wait in line to buy tickets to watch a documentary film, in the knowledge that the information provided will not hold instrumental value. In fact, there have been a number of empirical studies showing that humans (and even some animals) will incur a cost to receive information that is not instrumental to receiving rewards [2,3•,4,5].

The motivational power of curiosity may be even stronger. The dangerous strength of curiosity is a common theme in proverb and myth — it killed the cat, had Adam and Eve thrown from the Garden of Eden, and was responsible for Pandora releasing all the evils of the world. Indeed, curiosity has been found to predict risky behaviors such as initiation of smoking [6,7] and exposure to electric shocks [8,9••]; as well as exposure to information that is likely to result in negative affect [10,11••].

Understanding the mechanisms that drive human information seeking is a core aim across a number of fields including education, neuroscience, and decision science; yet these examples of seemingly irrational information seeking are somewhat puzzling to psychologists and behavioral economists who expect humans to maximize rewards. To understand such information-seeking behavior, one emerging consensus from the fields of psychology, neuroscience, and computational cognitive science is that information contains inherent rewarding value [12•,13]. Specifically, these behaviors may be accounted for by cognitive mechanisms that boost the value of exploring options with high information potential. However, considering the risks that people will take for information, it is possible that there is another distinct mechanism underlying the strong motivational force of curiosity.

In the current article, we first review emerging empirical studies that demonstrated the strong motivational lure of curiosity. Then we suggest that the seductive lure of curiosity may reflect an additional motivational mechanism that has been discussed in the literature of reward learning: *incentive salience*. We suggest that in addition to 'cognitive desire', the expectation of enjoyment from receiving new information, humans also experience a strong motivational pull toward information that is not related to hedonic experience. Indeed, this motivational state can even drive us to seek information that is dangerous or unpleasant.

Humans and animals pay for non-instrumental information

A number of recent studies have shown that people will pay to resolve uncertainty, even when the information they receive is not instrumental to their task performance. Humans [2,3•,14], crows [4], and monkeys [15,16] are all willing to pay to receive advance information about upcoming probabilistic rewards. For example, both Bennett *et al.* [2] and Rodriguez Cabrero *et al.* [3•] adapted the 'observation paradigm' from the animal literature, in which information about upcoming rewards can be received in advance at a cost. In both studies, human participants played a computerized card game and received monetary rewards for certain combinations of cards. Participants could pay a small cost to observe the cards early, and thus learn about their upcoming rewards sooner. Critically, the information they received could not alter their rewards. Nevertheless, participants in both studies were willing to spend money to receive advance knowledge about gamble outcomes. Humans are also willing to spend money, time, and effort to receive non-instrumental information that is unrelated to monetary rewards, such as answers to trivia questions. For example, Kang [17] found that participants were willing to wait for answers to trivia questions, and waited longer when they felt more curious.

Another line of research has examined the effect of outcome valence on information-seeking behavior. The effects of outcome valence are mixed, with evidence that people seek both positive and negative information. For example, Marvin and Shohamy [18] found that people were more likely to wait for the answers to trivia questions that they rated as positive or negative than for questions they rated as neutral. Similarly, van Lieshout, Traast, de Lange, and Cools [19] found that curiosity increased with increasing uncertainty about both expected gains and expected losses in a gambling task. Thus, it seems that although positive information may be preferred to negative information in some contexts [14], information can have a strong motivational lure regardless of the expected emotional impact of the information.

Curiosity trumps expected negative consequences

Further evidence that information is strongly motivational comes from examples of people seeking information that is expected to have negative consequences. Many recent studies have indicated that humans are willing to expose themselves to negative consequences in order to gain information. The concept of morbid curiosity describes the phenomenon of people desiring information that has negative valence, for example, wishing to learn about the gory details of a violent crime.

Oosterwijk [11••] investigated people's desire for negative information using a picture-viewing task in which participants chose to enlarge one of two thumbnail images independently rated as negative, neutral, or positive. Participants chose to view negative images (including open wounds, war scenes, and natural threats) over neutral and even positive images at least 30% of the time across a number of different conditions, and sometimes more often than neutral images. Further investigation of this phenomenon has shown that such negative choices involve greater neural activation in areas associated with reward than positive choices, suggesting that greater reward value may be assigned to negative information to overcome the expected negative emotional consequences [20].

People also subject themselves to physical harm to resolve curiosity. Hsee and Ruan [8] found that participants would risk receiving electric shocks by clicking joke pens some of which gave small shocks [21]. Participants were more likely to click the pens when uncertainty was high: that is, when they only knew that there was a mixture of shock and no-shock pens, but not which was which. Thus, the information gained by clicking the pen (learning whether the pen gave a shock or not) apparently outweighed the unpleasant experience of getting a shock. The effect replicated across hearing aversive sounds (fingernails on a chalkboard) and seeing unpleasant images (insects).

Lastly, people seek information in the knowledge that gaining it will make them feel bad. For example, FitzGibbon, Komiya, and Murayama [22] gave participants the opportunity to seek information about how much they could have won in a sequential risk-taking task (Balloon Analogue Risk Task [23]). This is an interesting context in which to study information seeking because participants were unlikely to have exactly reached the computers' randomly generated safe point on each trial, so there is a high chance that the information gained will lead to regret — they could have won more. Across a series of studies, participants would expend physical effort, accept a time penalty, and even pay money for this information that was of no future utility and made them feel worse than if they had not sought it.

Incentive salience as a complementary system to drive information-seeking behavior

In the literature of reward-learning of extrinsic incentives such as food, drugs, and money, Berridge *et al.* argued that *incentive salience* plays an important part of reward learning [24–26]. Incentive salience refers to the motivational feeling of 'wanting' in anticipation of an outcome that can be separated from the hedonic response of 'liking' to the outcome itself. This separation of 'wanting' and 'liking' can explain effortful pursuit of an outcome that does not lead to hedonic pleasure, as is observed in drug addiction [27]. These distinct motivational factors occur at different times — 'wanting' occurs in anticipation of an outcome, whereas 'liking' can only occur in response to consumption of the outcome (see Ref. [28]).

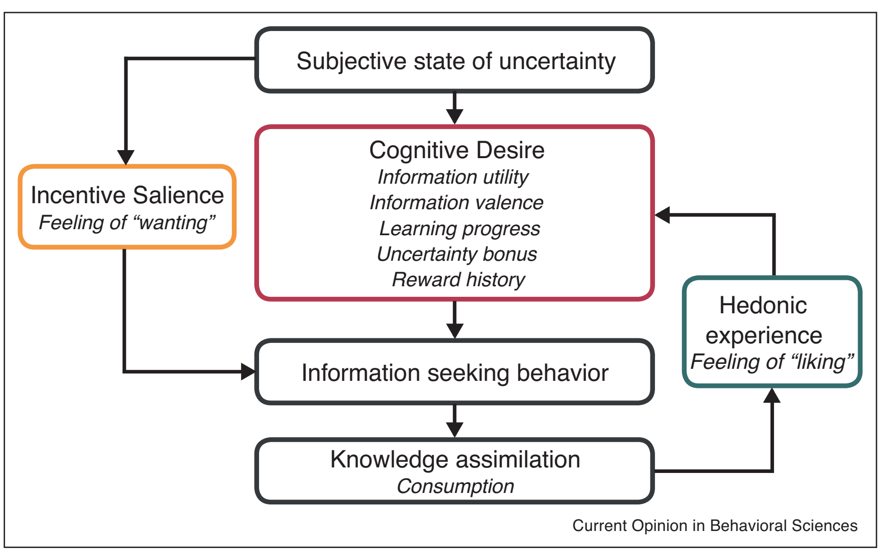
Berridge *et al.* also argued that anticipation of an outcome such as food entails *expected* pleasantness of the food, which is a cognitive evaluation of the value of the outcome based on past learning. Berridge called this valuation 'cognitive desire' and distinguished it from incentive salience [29,30]. Both incentive salience and cognitive desire are activated when one anticipates a rewarding outcome but two critical differences are that incentive salience (1) involves a strong motivational urge for immediate consumption, and (2) is sensitive to the physiological state of the agent, such as hunger.

As indicated earlier, recent research on curiosity has taken a reward-learning perspective to understand information-seeking behavior [13], pointing to a number of similarities in behavioral regulation and neural responses between extrinsic rewards such as money or food and knowledge acquisition. We propose that, like extrinsic rewards, information seeking is also supported by both cognitive desire and incentive salience. In the case of knowledge acquisition, cognitive desire represents the value of knowledge computed by a myriad of contextual factors. The expected reward value is thought to be boosted by the amount of uncertainty [31], learning progress [1,32], savoring the anticipation of positive information [33•], and generalization from previous positive experiences [34,35]. One commonality of these perspectives is that agents are posited to cognitively appraise (either explicitly or implicitly) the rewarding value of the new knowledge and make a decision based on this predicted rewarding value. Such cognitive desire well explains people's information-seeking behavior in the tasks that do not entail any real risk of negative consequences. However, we suggest that it is the incentive salience component that explains the strong seductive lure of curiosity — the motivational urge that drives people to engage in irrational, impulsive knowledge acquisition behavior.

In Figure 1 we have mapped out incentive salience and cognitive desire as distinct mechanisms in the knowledge acquisition process. The process begins with a subjective state of uncertainty. The agent's cognitive desire for the missing information is computed by combining the many contextual factors listed above. This cognitive evaluation is supported by incentive salience - a purely motivational urge for the information. Together, the strength of these two factors predicts whether information seeking will occur. Analogous with models of food seeking, we suggest that assimilation of new knowledge into the agent's existing knowledge base is 'consumption' of the knowledge that can elicit hedonic experience and feed back into the reward history of the information-seeking process.

The idea that curiosity involves incentive salience is not new. For example, Fowler [36] proposed that exploration is related to two distinct motivational factors: drive and incentive. More recently, Litman [37,38] described two different types of curiosity motivated by two different factors — interest and deprivation — that he likens to 'liking' and 'wanting' respectively. Interest-type (I-type) curiosity can be thought of as the motivation to gain information for the sake of its pleasantness. In contrast,

Figure 1



The knowledge acquisition process as reward learning supported by incentive salience. In the model, subjective states of uncertainty lead to both incentive salience and cognitive desire, which both in turn contribute to initiation of information-seeking behavior. Knowledge assimilation then occurs which leads to hedonic experience if the new knowledge is deemed satisfactory. That hedonic experience in turn feeds into the cognitive evaluation of future states of uncertainty.

deprivation-type (D-type) curiosity can be thought of as the intense motivational feeling to resolve the lack of needed information. Evidence for separable traits (i.e. individual differences) relating to the I-type and D-type curiosity has been found using questionnaire measures [39–41].

In addition to the behavioral studies reviewed above, further supportive evidence for the incentive salience hypothesis comes from neuroimaging studies. Previous work in humans has indicated that processing extrinsic rewards cues (e.g. food cues) involves the brain's reward network, especially the ventral striatum (i.e. the nucleus accumbens) and the dorsal striatum (i.e. the caudate nucleus). These findings suggest that incentive salience may be coded in these subcortical brain areas. Critically, some recent studies have shown that the subjective experience of curiosity is also associated with activation in these subcortical reward areas in the brain [17,42,43].

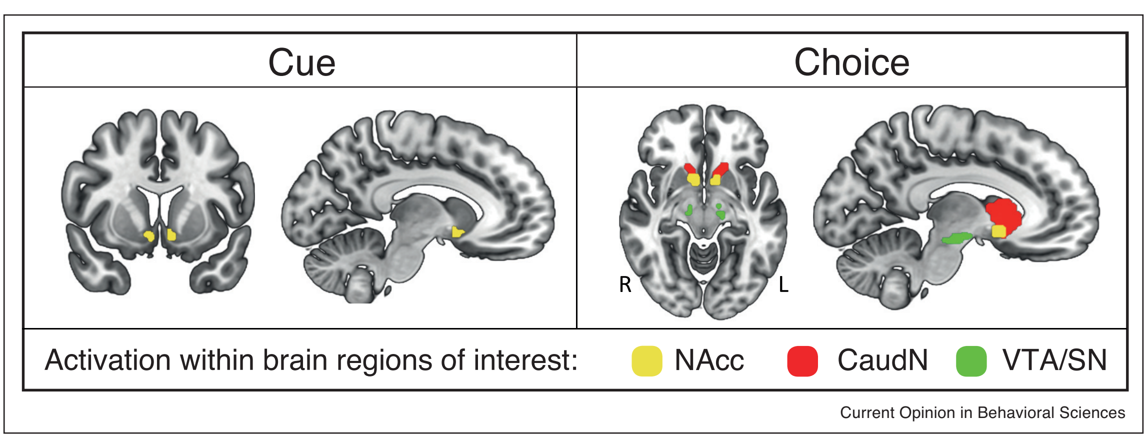
Of course, these brain activations may simply reflect the cognitive desire of knowledge acquisition. However, Lau *et al.* [9••] showed that the activation in these subcortical areas predict risky decision making based not only on extrinsic incentives (i.e. food) but also curiosity. The authors examined participants' neural responses (with functional magnetic resonance imaging) to food cues and to curiosity inducing cues (magic tricks or trivia questions) as well as their willingness to risk electric shocks to receive the cued food items or the solutions to the magic tricks or trivia questions. In trials when participants accepted the risk of electric shocks to satisfy hunger or curiosity (as opposed to trials when they rejected the risk) there was shared activation between food cues and curiosity inducing cues in a number of subcortical regions both at the time of cue presentation and when they made a decision (see Figure 2). These findings indicate a common motivational role of these subcortical brain areas to seduce risky decision making based on food and knowledge acquisition.

The incentive salience hypothesis also makes the unique prediction that motivation would be stronger for information that can be 'consumed' immediately, rather than for information that will be gained in the future. This feature of incentive salience has indeed been found in information seeking. In a creative set of studies, Kruger and Evans [10] showed that people will seek information that makes them feel bad, for example, by eavesdropping on conversations about themselves even when they expect what they hear to be derogatory. Critically, they also showed that people were more willing to seek negative information when it would be given immediately than in the future, and when it was for themselves rather than for someone else. These qualities of negative information seeking are resonant with a strong motivational urge (i.e. incentive salience) for the information rather than a cognitive evaluation of the information to be gained [44].

Summary and future directions

One critical feature of incentive salience, which distinguishes it from cognitive desire, is its dependency on physiological state [45,46]. For example, incentive salience of food is supposed to be magnified when one is hungry whereas cognitive desire is not. It is a challenge for an incentive salience account of information seeking to determine a physiological state that intensifies the motivational lure of information. Previous theoretical literature indicated that uncertainty or knowledge gaps cause this state of deprivation [37,47] but since awareness of uncertainty is the starting point for both cognitive desire and incentive salience (Figure 1), it is still unclear how this can help to disentangle incentive salience from

Figure 2



Shared reward network activation between food cues and information cues at the time of cue presentation and risky choice. Brain regions of interest within the reward network are: nucleus accumbens (NAcc); caudate nucleus (CaudN); and ventral tegmental area/substantia nigra (VTA/SN). Adapted with permission from Lau *et al.* [9••].

cognitive desire. Furthermore, the relationship between the size of the knowledge gap (uncertainty) and information-seeking behavior is very inconsistent in the empirical literature, with some showing stronger curiosity when one feels close to filling a knowledge gap [48,49,50•] (although not when one feels temporally close [51•]), whereas others demonstrated that an intermediate level of knowledge [17,52], or even a large knowledge gap [53•,54] causes motivation for information-seeking behavior (see Ref. [55] for a recent synthesis of some of these diverse findings). Future studies should examine the mechanisms that instigate the incentive salience property of curiosity.

Another important avenue for future research is to examine potential differences between different types of rewards. While there is evidence that primary rewards, such as food, and information rewards share neural underpinnings [9••], we also expect there to be differences in reward processing between primary rewards and information. For example, while consumption of food can lead to satiation, and thus cessation of food seeking, consumption of information can, in fact, sometimes lead to the recognition of new knowledge gaps. These new knowledge gaps, or questions can then motivate further information seeking, and so knowledge acquisition can form a positive feedback loop, making the information-seeking behavior sustainable [13].

Future research should also continue to examine the large intra-individual and inter-individual differences in the motivational lure of information and the antecedents of curiosity [33•,56–58]. Individual differences in the incentive salience responses to cues associated with extrinsic rewards have been linked to a number of clinical disorders in humans [59,60]. Similarly, individual differences in people's affective and behavioral responses to uncertainty have been related to a number of clinical diagnoses, including anxiety and depression (see Ref. [61]). Thus, better understanding of the neural and cognitive pathways associated with people's responses to uncertainty and information gaps may be of clinical importance to understanding these emotional disorders.

In summary, the incentive salience hypothesis makes a number of unique predictions about information seeking, many of which are born out in the extant literature and cannot be explained by traditional psychological and economic theories. First, it posits that it is possible to feel a strong motivational urge for information, even in the absence of expected hedonic experience upon receiving it. This is seen in examples of morbid curiosity [10,11••], costly curiosity [2,3•,22], and high-risk curiosity [8,9••]. Second, it predicts that immediately available information will be more motivationally salient than information that will be available in the future. While little work has examined the inter-temporal choices that people make while information seeking, there is some evidence that people are more motivated for immediate than distal rewards [10]. Finally, incentive salience is moderated by physiological state. This poses the greatest challenge for the account, but a state of uncertainty seems a likely candidate to moderate the motivational lure of information seeking.

Conflict of interest statement

Nothing declared.

CRediT authorship contribution statement

Lily FitzGibbon: Writing - original draft, Writing - review & editing, Visualization. **Johnny King L Lau:** Conceptualization, Writing - review & editing. **Kou Murayama:** Supervision, Funding acquisition, Conceptualization, Writing - review & editing.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Gottlieb J, Oudeyer PY: **Towards a neuroscience of active sampling and curiosity**. *Nat Rev Neurosci* 2018, **19**:758-770.

2. Bennett D, Bode S, Brydevall M, Warren H, Murawski C: **Intrinsic valuation of information in decision making under uncertainty**. *PLoS Comput Biol* 2016, **12**.

3. • Rodriguez Cabrero JAM, Zhu J-Q, Ludvig EA: **Costly curiosity: people pay a price to resolve an uncertain gamble early**. *Behav Processes* 2019, **160**:20-25

This study provides a clear demonstration of the motivational power of curiosity. Participants were willing to pay to receive immediate information about upcoming gamble outcomes despite its lack of utility.

4. Vasconcelos M, Monteiro T, Kacelnik A: **Irrational choice and the value of information**. *Sci Rep* 2015, **5**:13874.

5. Wang MZ, Hayden BY: **Monkeys are curious about counterfactual outcomes**. *Cognition* 2019, **189**:1-10.

6. Nodora J, Hartman SJ, Strong DR, Messer K, Vera LE, White MM, Portnoy DB, Choiniere CJ, Vullo GC, Pierce JP: **Curiosity predicts smoking experimentation independent of susceptibility in a US national sample**. *Addict Behav* 2014, **39**:1695-1700.

7. Pierce JP, Distefan JM, Kaplan RM, Gilpin EA: **The role of curiosity in smoking initiation**. *Addict Behav* 2005, **30**:685-696.

8. Hsee CK, Ruan B: **The Pandora effect: the power and peril of curiosity**. *Psychol Sci* 2016.

9. •• Lau JKL, Ozono H, Kuratomi K, Komiya A, Murayama K: **Shared striatal activity in decisions to satisfy curiosity and hunger at the risk of electric shocks**. *Nat Hum Behav* 2020 http://dx.doi.org/10.1038/s41562-020-0848-3

This important study compared people's willingness to take risks for two types of reward: food and information (solutions to magic tricks and answers to trivia questions). People were willing to take similar risks for food and information rewards. Crucially, patterns of brain activation were also found to be similar between extrinsic food rewards and information. Together this suggests that related motivational factors may operate for information and extrinsic rewards such as food.

10. Kruger J, Evans M: **The paradox of Alypius and the pursuit of unwanted information**. *J Exp Soc Psychol* 2009, **45**:1173-1179.

11. •• Oosterwijk S: **Choosing the negative: a behavioral demonstration of morbid curiosity**. *PLoS One* 2017, **12**:e0178399

This is an important demonstration of morbid curiosity - the seemingly irrational choice to expose oneself to negative or unpleasant information. In a series of studies the authors examine people's propensity to choose to expose themselves to negative images, such as images of dead bodies, graphic images of bodily harm, and images of natural threats such as snakes and spiders. On each trial, participants viewed two small thumbnail images or verbal descriptions of the images and selected an image to view enlarged on the screen for 4 s. Participants chose to look at the negative images on at least 30% of trials across a number of different conditions including conditions in which the alternative was rated to be positive rather than neutral.

12. • Gruber MJ, Ranganath C: **How curiosity enhances hippocampus-dependent memory: the prediction, appraisal, curiosity, and exploration (PACE) framework**. *Trends Cogn Sci* 2019, **23**:1014-1025

In this theoretical paper, the authors call upon recent evidence from the neuroscientific literature to support a new framework for understanding curiosity and its relationship with learning and memory. The cognitive and neural mechanisms that may support this relationship are explored and testable predictions for future work are proposed. Importantly, these authors highlight the role of the reward network in information seeking.

13. Murayama K, FitzGibbon L, Sakaki M: **Process account of curiosity and interest: a reward-learning perspective**. *Educ Psychol Rev* 2019, **31**:875-895.

14. Charpentier CJ, Bromberg-Martin ES, Sharot T: **Valuation of knowledge and ignorance in mesolimbic reward circuitry**. *Proc Natl Acad Sci U S A* 2018, **115**:E7255-E7264.

15. Bromberg-Martin ES, Hikosaka O: **Midbrain dopamine neurons signal preference for advance information about upcoming rewards**. *Neuron* 2009, **63**:119-126.

16. Bromberg-Martin ES, Hikosaka O: **Lateral habenula neurons signal errors in the prediction of reward information**. *Nat Neurosci* 2011, **14**:1209-1216.

17. Kang MJ, Hsu M, Krajbich IM, Loewenstein G, McClure SM, Wang JT-y, Camerer CF: **The wick in the candle of learning: epistemic curiosity activates reward circuitry and enhances memory**. *Psychol Sci* 2009, **20**:963-973.

18. Marvin CB, Shohamy D: **Curiosity and reward: valence predicts choice and information prediction errors enhance learning**. *J Exp Psychol: Gen* 2016, **145**:266-272.

19. van Lieshout L, Traast I, de Lange F, Cools R: **[Preprint] Curiosity or savouring? Information seeking is modulated by both uncertainty and valence**. *PsyArXiv* 2019.

20. Oosterwijk S, Snoek L, Tekoppele J, Engelbert L, Scholte HS: **Choosing to view morbid information involves reward circuitry**. *bioRxiv* 2019:795120.

21. Wilson TD, Reinhard DA, Westgate EC, Gilbert DT, Ellerbeck N, Hahn C, Brown CL, Shaked A: **Just think: the challenges of the disengaged mind**. *Science* 2014, **345**:75.

22. FitzGibbon L, Komiya A, Murayama K: *The Lure of Counterfactual Curiosity: People Incur a Cost to Experience Regret*. OSF Preprint; 2019.

23. Lejuez CW, Read JP, Kahler CW, Richards JB, Ramsey SE, Stuart GL, Strong DR, Brown RA: **Evaluation of a behavioral measure of risk taking: the Balloon Analogue Risk Task (BART)**. *J Exp Psychol: Appl* 2002, **8**:75.

24. Anselme P, Robinson MJF: **Incentive motivation: the missing piece between learning and behavior**. In *The Cambridge Handbook of Motivation and Learning.* Edited by Renninger KA, Hidi S. 2019:163-182.

25. Berridge KC: **From prediction error to incentive salience: mesolimbic computation of reward motivation**. *Eur J Neurosci* 2012, **35**:1124-1143.

26. Zhang J, Berridge KC, Tindell AJ, Smith KS, Aldridge JW: **A neural computational model of incentive salience**. *PLoS Comput Biol* 2009, **5**:e1000437.

27. Robinson TE, Berridge KC: **The incentive sensitization theory of addiction: some current issues**. *Philos Trans R Soc B: Biol Sci* 2008, **363**:3137-3146.

28. Pool E, Sennwald V, Delplanque S, Brosch T, Sander D: **Measuring wanting and liking from animals to humans: a systematic review**. *Neurosci Biobehav Rev* 2016, **63**:124-142.

29. Berridge KC: **Wanting and liking: observations from the neuroscience and psychology laboratory**. *Inquiry* 2009, **52**:378-398.

30. Berridge KC, Ho C-Y, Richard JM, DiFeliceantonio AG: **The tempted brain eats: Pleasure and desire circuits in obesity and eating disorders**. *Brain Res* 2010, **1350**:43-64.

31. Speekenbrink M, Konstantinidis E: **Uncertainty and exploration in a restless bandit problem**. *Top Cogn Sci* 2015, **7**:351-367.

32. Kaplan F, Oudeyer P-Y: **Maximizing learning progress: an internal reward system for development**. In *Embodied Artificial Intelligence: International Seminar, Dagstuhl Castle, Germany, July 7-11, 2003. Revised Papers.* Edited by Iida F, Pfeifer R, Steels L, Kuniyoshi Y. Springer Berlin Heidelberg; 2004:259-270.

33. • Kobayashi K, Ravaioli S, Baranès A, Woodford M, Gottlieb J: **Diverse motives for human curiosity**. *Nat Hum Behav* 2019, **3**:587-595

This study highlights the heterogeneity in people's motives for seeking information. Participants chose to receive information about one of two gambles that differed in the expected value and uncertainty of the outcome. Computational models fit to each individual suggested that individuals differed in their preference for resolving uncertainty and for receiving positive information (savoring).

34. Schulz E, Gershman SJ: **The algorithmic architecture of exploration in the human brain**. *Curr Opin Neurobiol* 2019, **55**:7-14.

35. Schulz E, Wu CM, Huys QJM, Krause A, Speekenbrink M: **Generalization and search in risky environments**. *Cogn Sci* 2018, **42**:2592-2620.

36. Fowler H: **Satiation and curiosity: constructs for a drive and incentive-motivational theory of exploration**. In *Psychology of Learning and Motivation*, , vol 1. Edited by Spence KW, Spence JT. Academic Press; 1967:157-227.

37. Litman JA: **Curiosity and the pleasures of learning: wanting and liking new information**. *Cogn Emotion* 2005, **19**:793-814.

38. Litman JA: **Curiosity: nature, dimensionality, and determinants**. In *Cambridge Handbook of Motivation and Learning.* Edited by Renninger KA, Hidi S. Cambridge University Press; 2019.

39. Litman JA: **Interest and deprivation factors of epistemic curiosity**. *Pers Individ Differences* 2008, **44**:1585-1595.

40. Litman JA, Crowson HM, Kolinski K: **Validity of the interest- and deprivation-type epistemic curiosity distinction in non-students**. *Pers Individ Differences* 2010, **49**:531-536.

41. Litman JA, Silvia PJ: **The latent structure of trait curiosity: evidence for interest and deprivation curiosity dimensions**. *J Pers Assess* 2006, **86**:318-328.

42. Gruber Matthias J, Gelman Bernard D, Ranganath C: **States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit**. *Neuron* 2014, **84**:486-496.

43. Kobayashi K, Hsu M: **Common neural code for reward and information value**. *Proc Natl Acad Sci U S A* 2019, **116**:13061.

44. Lades LK, Hofmann W: **Temptation, self-control, and inter-temporal choice**. *J Bioecon* 2019, **21**:47-70.

45. Berridge KC, Robinson TE: **What is the role of dopamine in reward: hedonic impact, reward learning, or incentive salience?** *Brain Res Rev* 1998, **28**:309-369.

46. Tindell AJ, Smith KS, Berridge KC, Aldridge JW: **Dynamic computation of incentive salience: "Wanting" what was never "Liked"**. *J Neurosci* 2009, **29**:12220.

47. Loewenstein G: **The psychology of curiosity: a review and reinterpretation**. *Psychol Bull* 1994, **116**:75-98.

48. Litman J, Hutchins T, Russon R: **Epistemic curiosity, feeling-of-knowing, and exploratory behaviour**. *Cogn Emotion* 2005, **19**:559-582.

49. Metcalfe J, Schwartz BL, Bloom PA: **The tip-of-the-tongue state and curiosity**. *Cogn Res: Princ Implic* 2017, **2**:31.

50. • Wade S, Kidd C: **The role of prior knowledge and curiosity in learning**. *Psychon Bull Rev* 2019, **26**:1377-1387
In this study, curiosity about trivia question answers was best predicted by how close the participant felt to the answer. The closer they thought they were, the more curious they were to learn the answer. This demonstrates that it is the subjective experience of the information gap that is important for the experience of curiosity. It also suggests that small information gaps may be more motivationally salient than larger gaps.

51. • Noordewier MK, van Dijk E: **Curiosity and time: from not knowing to almost knowing**. *Cogn Emotion* 2017, **31**:411-421
This series of experiments take a novel approach by manipulating the time to the resolution of uncertainty to investigate the effect of information gaps on people's curiosity and mood. Long time gaps were associated with more self-reported discomfort, but not more curiosity.

52. Baranes A, Oudeyer P-Y, Gottlieb J: **Eye movements reveal epistemic curiosity in human observers**. *Vis Res* 2015, **117**:81-90.

53. • van Lieshout LLF, Vandenbroucke ARE, Müller NCJ, Cools R, de Lange FP: **Induction and relief of curiosity elicit parietal and frontal activity**. *J Neurosci* 2018, **38**:2579
This study uses a novel lottery task to disentangle the contributions of uncertainty and expected value of upcoming rewards. Curiosity (self-reported and willingness to wait) increased with uncertainty about the reward outcome but was not affected by the expected value of reward.

54. Kidd C: **Computational models for understanding curiosity throughout development**. *Exploring Curiosity*. 2018. Edited by. Amsterdam.

55. Dubey R, Griffiths T: **Reconciling novelty and complexity through a rational analysis of curiosity**. *PsyArXiv* 2019.

56. Fastrich GM, Kerr T, Castel AD, Murayama K: **The role of interest in memory for trivia questions: an investigation with a large-scale database**. *Motiv Sci* 2017. No Pagination Specified-No Pagination Specified.

57. Litman JA, Mussel P: **Validity of the interest-and deprivation-type epistemic curiosity model in Germany**. *J Individ Differences* 2013, **34**:59-68.

58. Lydon-Staley DM, Zhou D, Sizemore Bevins A, Zurn P, Bassett DS: **Hunters, busybodies, and the knowledge network building associated with curiosity**. *PsyArXiv* 2019.

59. Olney JJ, Warlow SM, Naffziger EE, Berridge KC: **Current perspectives on incentive salience and applications to clinical disorders**. *Curr Opin Behav Sci* 2018, **22**:59-69.

60. Jones DN, Neria AL: **Incentive salience & psychopathy: a bio-behavioral exploration**. *Pers Individ Differences* 2019, **138**:167-176.

61. Carleton RN: **Into the unknown: a review and synthesis of contemporary models involving uncertainty**. *J Anxiety Disord* 2016, **39**:30-43.