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Why so curious? Quantifying mechanisms of information seeking

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Humans devote a substantial part of their time to seeking and consuming information. Often, this information is directly relevant. However, we also seek out information without obvious direct purpose. Curiosity about this type of information is called 'non-instrumental curiosity'. In this review we ask why we are so curious about information that serves no direct purpose and address the psychological and neural mechanisms by which such apparently purpose-less curiosity is elicited. Non-instrumental curiosity is argued to fulfill (at least) two goals: to progressively reduce uncertainty about the world around us, and to accrue information that makes us feel good. We conclude by highlighting the promise of future psychopharmacological and neurochemical imaging studies of curiosity for elucidating the basis of both state and trait-related variation in curiosity. This is pertinent given the key implication of neurotransmitters like noradrenaline and dopamine in uncertainty reduction, reward motivation and cognitive effort.

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Introduction

In our everyday lives, we spend an enormous amount of time seeking and consuming information. From time to time, we can directly use this information, for example, when checking the weather report before leaving the house to see if we should take an umbrella. When looking for such information that is directly relevant, we aim to maximize reward and/or to minimize harm (i.e. not arriving at work completely soaked; [1]). This type of information seeking can also be called 'goal directed exploration' or 'instrumental curiosity' (see also Refs. [2,3•]).

Critically, humans and other animals are also known to seek out information without such obvious purpose in mind. Think, for example, about situations in which we scroll through our Instagram feed or check our Facebook, without a specific purpose. This type of curiosity is often referred to as 'non-instrumental curiosity' (see also Ref. [3•]). Considering the amount of time we spend consuming such non-instrumental information, a relevant question is why we are so curious about information that serves no direct obvious purpose. What are the psychological and neural mechanisms by which such apparently purpose-less curiosity is elicited?

Here, we provide an overview of the recent cognitive and neuroscientific literature on non-instrumental curiosity. For reviews on goal-directed exploration and instrumental curiosity, we refer the reader to other sources (i.e. Refs. [4–6]). In short, we argue that non-instrumental curiosity might serve at the least the following purposes: [1] to reduce uncertainty about the world around us, [2] to make us feel good (savouring). Thus, curiosity is a function of multiple motives that are not mutually exclusive and likely go hand-in-hand (Figure 1).

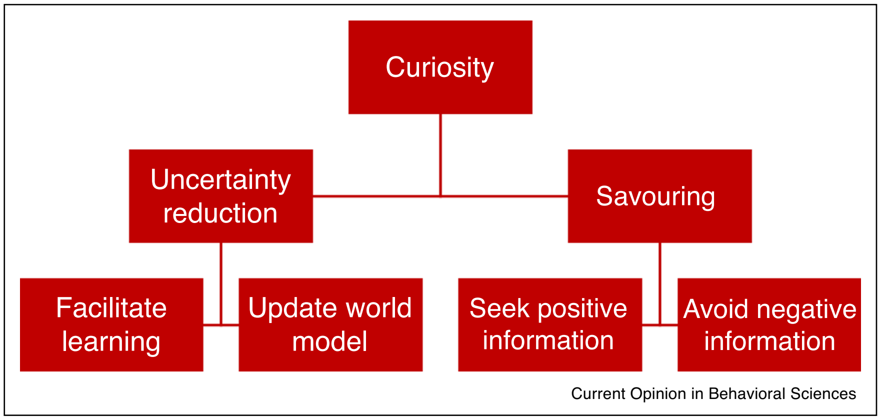
Curiosity and uncertainty reduction

Decades ago, Berlyne [7] already observed that humans seek out information or stimulation for its own sake. Such exploration is particularly triggered in situations that include novelty, surprise, incongruity and complexity. In fact, people are especially curious about stimuli with intermediate levels of novelty [8]. One reason for this preference might be that stimuli that are not familiar but also not completely new may have the highest potential for providing learning opportunities. In other words: they are most likely to reduce uncertainty about the world around us.

Curiosity motivates learning

Curiosity can be defined as the 'intrinsic motivation to learn and to acquire information'. Therefore, curiosity has long been argued to play a central role in development, learning and exploration (i.e. Refs. [3•,9–11,12••]). This view was inspired by Loewenstein, who described curiosity as a 'cognitive induced deprivation that arises from the perception of a gap in knowledge and understanding' [12••]. He argued that curiosity is essentially an aversive drive that arises when people become aware of gaps in their knowledge. People are driven to fill these gaps with information, which is in turn often considered to be rewarding.

Figure 1



In this review we argue that non-instrumental curiosity serves at least two purposes. The first is that it progressively reduces uncertainty about the world around us. By means of uncertainty reduction, curiosity facilitates learning and it updates our current model of the world. The second purpose is that we accrue information that makes us feel good (savouring). In other words: we tend to seek positive information and tend to avoid negative information.

Evidence for the notion that humans and other animals are driven by information comes from recent studies with nonhuman primates (macaque monkeys). In these studies, monkeys had the opportunity to choose to receive information about upcoming primary rewards (such as water or juice; [13••,14]). Results showed that monkeys more often choose an informative than an uninformative option, even though this choice did not alter the likelihood of actually receiving the reward. More strikingly, monkeys were even willing to give op a substantial portion of their reward in order to get this information [15•]. Information and primary reward were shown to implicate the same neural structures: Cells coding for the reward prediction error also coded for an information prediction error, that is, the difference between expected information and received information. In fact, such information prediction errors were found in midbrain dopamine neurons (DA neurons) as well as in lateral habenula (LHb) neurons [13••,14]. These findings are supported by work with human volunteers, showing that humans are also willing to incur considerable monetary costs to acquire early information that had no obvious purpose [16–18]. In addition, Brydevall *et al.* [17] found using EEG that feedback-related negativity independently encoded both an information prediction error as well as a reward prediction error. This is consistent with the hypothesis that information is processed in neural reward circuitries and supports the information-as-reward hypothesis. In other words: people show a strong preference for information, and information might be rewarding in and of itself.

Further support for the information-gap hypothesis [12••] comes, for example, from Jepma *et al.* (see Ref [46]), who showed participants blurry photos with ambiguous contents that piqued their curiosity. Next, participants' curiosity was either relieved by revealing the actual picture or not. Curiosity was associated with activation of the anterior cingulate cortex (ACC) and the anterior insula, regions that are sensitive to aversive conditions (but also many other things, such as conflict and arousal). Resolution of curiosity was associated with activity in regions of the striatum that have been related to reward processing, while also enhancing hippocampal activation and incidental memory. Consistent with the proposal by Loewenstein, these data led to the conclusion that curiosity is marked by an aversive state of lacking information. This unpleasant state motivates information seeking, which alleviates this aversive state and facilitates memory.

In addition, studies in which human volunteers were presented with trivia questions [9,19••,20,21,22••] while undergoing fMRI [19••,20,21], support the notion that curiosity facilitates learning. In one of these studies, participants had to indicate how curious they were to learn the answer as well as how confident they were that they knew the answer [20]. Participants were most curious about trivia questions with intermediate levels of confidence. Unsurprisingly, they were not curious about questions for which they either already knew the answer (when there was no information gap) or about questions for which they were not confident at all (when the information gap was too large). In addition, people were more willing to wait and pay for information about which they were more curious and curiosity enhanced later recall of novel information. This was supported by findings of Gruber *et al.* [19••] who found, using a similar paradigm, that participants showed better learning in states of high compared to low curiosity. Additionally, learning was driven by the gap between the actual value of the information received and the anticipated value of the information (curiosity); the so-called information prediction error [22••]. These results support the idea that information functions as a reward.

Self-reported curiosity has been associated with brain activity in the caudate nucleus [20], the midbrain and the nucleus accumbens [19••]. These are structures that are more generally activated by reward anticipation, suggesting that curiosity elicits a so-called 'anticipation of reward' state (consistent with Loewenstein's theory). Curiosity-driven memory benefits correlated with anticipatory activity in midbrain and hippocampus [19••] and when the answer to trivia questions was revealed, activations were found in structures associated with learning and memory, such as the parahippocampal gyrus and hippocampus [20]. It should be noted that Jepma *et al.* [46] posit curiosity to be a fundamentally aversive state, whereas it is conceptualized as pleasurable and linked to reward anticipation in studies using trivia questions [19••,20]. It is surprising that the latter studies did not find ventral striatum responses to curiosity relief, a classic structure that responds to receipt of reward. However, in another study using a stochastic trivia questions paradigm (in which it was unpredictable whether the answer to a trivia question would be revealed), relief of curiosity did activate the ventral striatum [21]. It appears that the ventral striatum might, therefore, not be related to reception of knowledge per se, but it may be selectively recruited when curiosity is relieved in a stochastic fashion (and thereby reflecting a form of a relief prediction error.

These results suggest that curiosity is supported by mechanisms that are similar to those implicated in incentive motivation and reward-based learning. To account for the evidence that curiosity states are related to modulations in the dopaminergic circuits and impact memory encoding, Gruber and Ranganath [23] put forward the hypothesis that curiosity is triggered by prediction errors that are appraised. This enhances memory encoding by means of heightened attention, exploration and information seeking, as well as the consolidation of information acquired in states of curiosity through dopaminergic modulation of the hippocampus (see Ref. [23], for more detailed neuroscientific mechanisms).

Curiosity promotes an update of one's world model

The literature reviewed above mainly focuses on curiosity, learning and its benefits for memory encoding. In these studies, obtaining information (for example, when receiving the answer to a trivia question) is itself rewarding, consistent with an information-as-reward hypothesis [12••,22••]. This information is likely rewarding to us, because it will help us to get a better idea about what is going on the world around us. In other words: it will help us to update our current model of the world.

In our recent work we have demonstrated that we are particularly curious about information when that information reduces uncertainty about the world around us and that this drive can even supersede the drive for explicit reward [24••]. The studies reviewed above show that both macaque monkeys and humans show a preference for information over no information [13••,14]. In our study, using a non-instrumental lottery task, we investigated whether people were also driven by the size of the information gap. In other words: does curiosity increase with uncertainty? To this end, we independently manipulated the amount of information that could be gained by seeing the outcome (outcome uncertainty) as well as the amount of reward that could be gained (expected value). We found that people are more curious and more willing to wait when there was higher uncertainty about the outcome, but not when expected value was higher ([25,26,24••], see also Ref. [18]). This induction of curiosity by outcome uncertainty was associated with activity in the parietal cortex, possibly because of the higher amount of attentional resources required to process situations that are marked by higher uncertainty ([24••], see also Ref. [27]). Relief of curiosity was associated with activity in the orbitofrontal cortex (OFC; see also Ref. [28••]) and the insula. Moreover, the insula also coded the size of the information update (information prediction error; see also Ref. [29]). These findings show that we are driven by uncertainty to update our current world model and that this drive can go beyond the drive for explicit rewards.

A related, but not mutually exclusive hypothesis comes from work in the field of developmental robotics. According to the learning progress hypothesis [30], humans are curious when there are opportunities to make learning progress. Specifically, curiosity is argued to increase, not with uncertainty or information prediction error (i.e. surprise) per se, but rather with the minimization of the derivative of (i.e. difference between two successive) prediction errors. This proposal is reminiscent of the predictive coding framework, according to which agents are driven to minimize surprise, and thus also information prediction errors [31]. This was reflected in the behavior of the robots, which first focus on situations that are easy to learn, before shifting attention to more difficult situations. At the same time, the robots avoided situations that were too complex and in which nothing could be learned. Similarly, infants also prefer to attend to stimuli of medium complexity and avoid attending to stimuli which are too difficult to learn from also in situations when there are no explicit rewards to be obtained [32].

Curiosity and savouring

In addition to reducing uncertainty, people may also seek information simply because it makes them feel good. In addition to reducing uncertainty about the world around us, we also exhibit a preference for positive over negative belief updating.

For instance, recent studies have indicated that people are generally more curious about positive information than about negative information. This has been demonstrated using trivia questions paradigms with people being more curious about questions with positive compared with negative valence [22••] as well as using more quantitative lottery tasks, showing that people are more curious about gains (positive information) compared with losses (losses; [25,26,28••])

In fact, from time to time we even deliberately decide to avoid information. Many people prefer not to be informed about things such as potential negative medical test results [33,34]. Human volunteers have been shown to be willing to pay not only for obtaining positive information, but also to avoid knowledge about negative information [28••]. The observation that this preference for advance knowledge about positive (versus negative) information is stronger when the outcome is further removed in the future has led to the conclusion that people seek information in order to maximize the state of reward anticipation, that is, savouring (versus dread; [35]). Charpentier *et al.* [28••] demonstrated that the desire to gain knowledge over ignorance is accompanied by neural signals in the orbitofrontal cortex (OFC; cf. [15•,24••]), regardless of valence. In addition, activity in the mesolimbic reward circuitry (VTN/SN) was modulated by the opportunity to gain knowledge about positive, but not negative outcomes (by coding valence-dependent information prediction errors). In accordance with this, they propose that the nucleus accumbens integrates a signal from the OFC (coding for the opportunity to obtain knowledge) with a valence-dependent value signal in the VTA/SN. In this way, greater information seeking is elicited when content is expected to be positive versus negative, explaining the preference for positive over negative belief updating.

Together these observations have led Sharot and Sunstein [36] to conclude that information can alter people's action, affect and cognition in both positive and negative ways. The suggestion is that people evaluate and integrate these influences, calculating the value of information leading to information seeking or avoidance. This offers a framework for identifying and quantifying how individuals differ in their information-seeking behavior.

Conclusion and open questions

We have argued that non-instrumental curiosity serves multiple purposes, and reflects both a motivation to form accurate beliefs (knowing) as well as a motivation to enter the positive state of reward anticipation (savouring). Most people show a combination of both drives and the mixture of motives differs between individuals [37••,26,38]. Taking into account the work from developmental robotics and psychology, we argue that these drives of knowing and savouring likely intertwine with a third drive, that is, to make learning progress. Future work is needed to address this hypothesis, for example, using experimental designs where curiosity ratings and/or behaviors are measured on a trial-by-trial basis as a function of changes in the difference between the predicted and the obtained amount of information.

A second focus for future work might be to study of neuromodulatory drug effects on human curiosity behavior. This is pertinent, given the well-known role of the large ascending neuromodulators, such as dopamine and noradrenaline, in the various curiosity-relevant constructs highlighted here, such as uncertainty-based (meta-)learning (i.e. Refs. [39,40]), reward motivation and cognitive effort [41]. Prior evidence demonstrating that the firing of single dopamine neurons in the midbrain correlates with the size of the information prediction error [13••,14] further underscores the promise of human psychopharmacological interventions for studying the basis of both inter-individual and intra-individual variability in curiosity behavior.

A third line of focus for future work might be to study what drives curiosity for negative content. Though we argue in the current review that humans prefer positive over negative information, it should be noted that people were also curious and willing to wait for losses (albeit to a lesser degree than for gains), and more so when the uncertainty about these losses was higher [26]. This resonates with findings indicating that people are curious about information that will likely lead to negative affect [42–45] and with the notion that people prefer to reduce uncertainty, even if it leads to negative experiences [43]. From time to time, people deliberately choose to view negative 'morbid' information, such as pictures of beheadings or violent social conflicts, and even choose such images over neutral ones [44]. One motive that might explain curiosity for such intense negative information is that it might be associated with high uncertainty (see Ref. [45]). In other words: humans might exhibit a general desire to reduce uncertainty and increase knowledge about what is going on, and that this drive can go over and above the potential unpleasantness of the information (such as losses or morbid information).

Conflict of interest statement

Nothing declared.

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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. Stigler GJ: **The economics of information**. *J Political Econ* 1961, **69**:213-225.

2. Daw ND, O'Doherty JP, Dayan P, Seymour B, Dolan RJ: **Cortical substrates for exploratory decisions in humans**. *Nature* 2006, **441**:876-879 http://dx.doi.org/10.1038/nature04766.

3. • Kidd C, Hayden BY: **The psychology and neuroscience of curiosity**. *Neuron* 2015, **88**:449-460 http://dx.doi.org/10.1016/j.neuron.2015.09.010.
This review paper highlights important work regarding the psychology and neuroscience of curiosity.

4. Addicott MA, Pearson JM, Sweitzer MM, Barack DL, Platt ML: **A primer on foraging and the explore/exploit trade-off for psychiatry research**. *Neuropsychopharmacology* 2017, **42**:1931-1939 http://dx.doi.org/10.1038/npp.2017.108.

5. Averbeck BB: **Theory of choice in bandit, information sampling and foraging tasks**. *PLoS Comput Biol* 2015, **11**:e1004164 http://dx.doi.org/10.1371/journal.pcbi.1004164.

6. Daw ND, Doya K: **The computational neurobiology of learning and reward**. *Curr Opin Neurobiol* 2006, **16**:199-204 http://dx.doi.org/10.1016/j.conb.2006.03.006.

7. Berlyne DE: **Curiosity and exploration**. *Science* 1966, **153**:25-33 http://dx.doi.org/10.1126/science.153.3731.25.

8. Berlyne DE: *Conflict, Arousal, and Curiosity*. New York, NY: Mc-Graw-Hill; 1960 http://dx.doi.org/10.1037/11164-000.

9. Baranes A, Oudeyer P-Y, Gottlieb J: **Eye movements reveal epistemic curiosity in human observers**. *Vision Res* 2015, **117**:81-90 http://dx.doi.org/10.1016/j.visres.2015.10.009.

10. Berlyne DE: **A theory of human curiosity**. *Brit J Psychol* 1954, **45**:180-191.

11. Gottlieb J, Oudeyer P-Y, Lopes M, Baranes A: **Information-seeking, curiosity, and attention: computational and neural mechanisms**. *Trends Cognit Sci* 2013, **17**:585-593 http://dx.doi.org/10.1016/j.tics.2013.09.001.

12. •• Loewenstein G: **The psychology of curiosity: a review and reinterpretation**. *Psychol Bull* 1994, **116**:75-98.
This important paper suggests that people become curious when they become aware of gaps in their knowledge.

13. •• Bromberg-Martin ES, Hikosaka O: **Midbrain dopamine neurons signal preference for advance information about upcoming rewards**. *Neuron* 2009, **63**:119-126 http://dx.doi.org/10.1016/j.neuron.2009.06.009.
This important paper shows that macaque monkeys are driven by information. It demonstrates that monkeys more often choose for an informative than for an uninformative option, even though this choice did not alter the likelihood of actually receiving the reward. The expected amount of information was signaled in midbrain dopamine neurons in a similar way as the expected amount of explicit reward.

14. Bromberg-Martin ES, Hikosaka O: **Lateral habenula neurons signal errors in the prediction of reward information**. *Nat Neurosci* 2011, **14**:1209-1216 http://dx.doi.org/10.1038/nn.2902.

15. • Blanchard TC, Hayden BY, Bromberg-Martin ES: **Orbitofrontal cortex uses distinct codes for different choice attributes in decisions motivated by curiosity**. *Neuron* 2015, **85**:602-614 http://dx.doi.org/10.1016/j.neuron.2014.12.050.
This elegant paper shows that macaque monkeys are willing to forego a large portion of reward to receive advance non-instrumental information.

16. Bennett D, Bode S, Brydevall M, Warren H, Murawski C: **Intrinsic valuation of information in decision making under uncertainty**. *PLoS Comput Biol* 2016, **12**:e1005020 http://dx.doi.org/10.1371/journal.pcbi.1005020.

17. Brydevall M, Bennett D, Murawski C, Bode S: **The neural encoding of information prediction errors during non-instrumental information seeking**. *Sci Rep* 2018, **8**:6134 http://dx.doi.org/10.1038/s41598-018-24566-x.

18. Rodriguez Cabrero JAM, Zhu JQ, Ludvig EA: **Costly curiosity: people pay a price to resolve an uncertain gamble early**. *Behav Processes* 2019, **160**:20-25 http://dx.doi.org/10.1016/j.beproc.2018.12.015.

19. •• Gruber MJ, Gelman BD, Ranganath C: **States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit**. *Neuron* 2014, **84**:486-496 http://dx.doi.org/10.1016/j.neuron.2014.08.060.
This paper shows, using a trivia questions paradigm, that humans show improved memory while in states of high curiosity which was accompanied by activity in the hippocampus. It highlights the mechanisms by which curiosity supports memory and learning.

20. Kang MJ, Hsu M, Krajbich IM, Loewenstein G, McClure SM, Wang JT, Camerer CF: **The wick in the candle of learning: epistemic curiosity activates reward circuitry and enhances memory**. *Psychol Sci* 2009, **20**:963-973 http://dx.doi.org/10.1111/j.1467-9280.2009.02402.x.

21. Ligneul R, Mermillod M, Morisseau T: **From relief to surprise: dual control of epistemic curiosity in the human brain**. *Neuroimage* 2017, **181**:490-500 http://dx.doi.org/10.1016/j.neuroimage.2018.07.038.

22. •• Marvin CB, Shohamy D: **Curiosity and reward: valence predicts choice and information prediction errors enhance learning**. *J Exp Psychol Gener* 2016, **145**:266-272 http://dx.doi.org/10.1037/xge0000140.
This paper shows, using a trivia questions paradigm, that we are more curious about positive compared with negative information. Additionally, it demonstrates that learning is driven by the information prediction error; the gap between the actual value of the received information and the anticipated value of the information. These results support the idea that information functions as a reward.

23. Gruber MJ, Ranganath C: **How curiosity enhances hippocampus-dependent memory: the prediction, appraisal, curiosity, and exploration (PACE) framework**. *Trends Cognit Sci* 2019, **23**:1014-1025 http://dx.doi.org/10.1016/j.tics.2019.10.003.

24. •• 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**:2579-2588 http://dx.doi.org/10.1523/JNEUROSCI.2816-17.2018.
This paper shows, using a novel lottery task, that curiosity is driven by the uncertainty of a lottery outcome, rather than by the expected value of rewards. The findings of this paper point towards the idea that we are driven by uncertainty to update our current world model and that this drive can go beyond the drive for explicit reward.

25. van Lieshout LLF, de Lange FP, Cools R: **Curiosity: an appetitive or an aversive drive?** *PsyArXiv* 2020 http://dx.doi.org/10.31234/OSF.IO/S3ZP4.

26. van Lieshout LLF, Traast IJ, de Lange FP, Cools R: **Curiosity or savouring? Information seeking is modulated by both uncertainty and valence**. *PsyArXiv* 2019 http://dx.doi.org/10.31234/OSF.IO/5Y6PZ.

27. Huettel SA, Song AW, Mccarthy G: **Decisions under uncertainty: probabilistic context influences activation of prefrontal and parietal cortices**. *J Neurosci* 2005, **25**:3304-3311 http://dx.doi.org/10.1523/JNEUROSCI.5070-04.2005.

28. •• Charpentier CJ, Bromberg-Martin ES, Sharot T: **Valuation of knowledge and ignorance in mesolimbic reward circuitry**. *PNAS* 2018, **115**:E7255-E7264 http://dx.doi.org/10.1073/pnas.1800547115.
This paper shows that we seek information that makes us feel good, but that we tend to avoid information that makes us feel bad. Specifically, the mesolimbic reward circuitry selectively treats the opportunity to gain knowledge about favorable, but not unfavorable outcomes as a reward.

29. Preuschoff K, Quartz SR, Bossaerts P: **Human insula activation reflects risk prediction errors as well as risk**. *J Neurosci* 2008, **28**:2745-2752 http://dx.doi.org/10.1523/JNEUROSCI.4286-07.2008.

30. Oudeyer P-Y, Kaplan F, Hafner VV: **Intrinsic motivation systems for autonomous mental development**. *IEEE Trans Evol Comput* 2007, **11**:265-286 http://dx.doi.org/10.1109/TEVC.2006.890271.

31. Friston KJ, Lin M, Frith CD, Pezzulo G, Hobson JA, Ondobaka S: **Active inference, curiosity and insight**. *Neural Comput* 2017, **29**:2633-2683 http://dx.doi.org/10.1162/NECO_a_00999.

32. Kidd C, Piantadosi ST, Aslin RN: **The Goldilocks effect: human infants allocate attention to visual sequences that are neither too simple nor too complex**. *PLoS One* 2012, **7**:e36399 http://dx.doi.org/10.1371/journal.pone.0036399.

33. Dwyer LA, Shepperd JA, Stock ML: **Predicting avoidance of skin damage feedback among college students**. *Ann Behav Med* 2015, **49**:685-695 http://dx.doi.org/10.1007/s12160-015-9703-6.

34. Persoskie A, Ferrer RA, Klein WMP: **Association of cancer worry and perceived risk with doctor avoidance: an analysis of information avoidance in a nationally representative US sample**. *J Behav Med* 2014, **37**:977-987 http://dx.doi.org/10.1007/s10865-013-9537-2.

35. Iigaya K, Story GW, Kurth-Nelson Z, Dolan RJ, Dayan P: **The modulation of savouring by prediction error and its effects on choice**. *eLife* 2016, **5**:e13747 http://dx.doi.org/10.7554/eLife.13747.001.

36. Sharot T, Sunstein CR: **How people decide what they want to know**. *Nat Hum Behav* 2020, **4**:14-19 http://dx.doi.org/10.1038/s41562-019-0793-1.

37. Kobayashi K, Ravaioli S, Baranès A, Woodford M, Gottlieb J:
•• **Diverse motives for human curiosity**. *Nat Hum Behav* 2019, **3**:587-595 http://dx.doi.org/10.1038/s41562-019-0589-3.
This paper shows, using a lottery task, that there are various motives that drive human curiosity. It shows that individuals are both motivated to form accurate beliefs, as well as to seek information that makes them feel good.

38. van Lieshout LLF, de Lange FP, Cools R: **Motives underlying human curiosity**. *Nat Hum Behav* 2019, **3**:550-551 http://dx.doi.org/10.1038/s41562-019-0565-y.

39. Nassar MR, Rumsey KM, Wilson RC, Parikh K, Heasly B, Gold JI: **Rational regulation of learning dynamics by pupil-linked arousal systems**. *Nat Neurosci* 2012, **15**:1040-1046 http://dx.doi.org/10.1038/nn.3130.

40. Wang JX, Kurth-Nelson Z, Kumaran D, Tirumala D, Soyer H, Leibo JZ, Hassabis D, Botvinick M: **Prefrontal cortex as a meta-reinforcement learning system**. *Nat Neurosci* 2018, **21**:860-868 http://dx.doi.org/10.1038/s41593-018-0147-8.

41. Westbrook A, van den Bosch R, Määttä JI, Hofmans L, Papadopetraki D, Cools R, Frank MJ: **Dopamine promotes cognitive effort by biasing the benefits versus costs of cognitive work**. *Science* 2020, **367**:1362-1366.

42. FitzGibbon L, Komiya A, Murayama K: **The lure of counterfactual curiosity: people incur a cost to experience regret**. *OSF Preprint* 2019 . Retrieved from *https://osf.io/jm3uc/*.

43. Hsee CK, Ruan B: **The Pandora effect: the power and peril of curiosity**. *Psychol Sci* 2016, **27**:659-666 http://dx.doi.org/10.1177/0956797616631733.

44. Oosterwijk S: **Choosing the negative: a behavioral demonstration of morbid curiosity**. *PLoS One* 2017, **12**:e0178399 http://dx.doi.org/10.1371/journal.pone.0178399.

45. Oosterwijk S, Snoek L, Tekoppele J, Engelbert L, Scholte HS: **Choosing to view morbid information involves reward circuitry**. *bioRxiv* 2019 http://dx.doi.org/10.1101/795120.

46. Jepma M, Verdonschot RG, van Steenbergen H, Rombouts SARB, Nieuwenhuis S: **Neural mechanisms underlying the induction and relief of perceptual curiosity**. *Front Behav Neurosci* 2012, **6**:1-9 http://dx.doi.org/10.3389/fnbeh.2012.00005.