Arousal, exploration and the locus coeruleus-norepinephrine system

Jepma, M.

Chapter 5

Neural mechanisms underlying the induction and relief of perceptual curiosity

This chapter is based on: Jepma, M., Verdonschot, R.G., Van Steenbergen, H., Rombouts, S.A., & Nieuwenhuis, S. (under review). Neural mechanisms underlying the induction and relief of perceptual curiosity.

Abstract

Curiosity is one of the most basic biological drives in both animals and humans, and has been identified as a key motive for learning and discovery. Despite the importance of curiosity and related behaviors, the topic has been largely neglected in human neuroscience; hence little is known about the neurobiological mechanisms underlying curiosity. We used functional magnetic resonance imaging (fMRI) to investigate what happens in our brain during the induction and subsequent relief of perceptual curiosity. Our core findings were that (i) the induction of perceptual curiosity, through the presentation of ambiguous visual input, activated the anterior insula and anterior cingulate cortex, brain regions sensitive to conflict and arousal; (ii) the relief of perceptual curiosity, through visual disambiguation, activated regions of the striatum that have been related to reward processing; and (iii) the relief of perceptual curiosity was associated with hippocampal activation and enhanced incidental memory. These findings provide the first demonstration of the neural basis of human perceptual curiosity. Our results provide compelling neurobiological support for a classic psychological theory of curiosity, which holds that curiosity is an aversive condition of increased arousal whose termination is rewarding and facilitates memory (Berlyne, 1954).

Introduction

Curiosity is one of the most basic biological drives in both animals and humans, and has been identified as a key motive for learning and discovery. In the 1950's and 60's, curiosity and related behaviors were topics of intense investigation among experimental psychologists, resulting in an extensive theoretical framework for understanding curiosity and related behaviors (e.g., Berlyne, 1954; Berlyne, 1960; Berlyne, 1966; Loewenstein, 1994). According to a classic psychological theory of curiosity, developed by Berlyne (1954), curiosity evoked by ambiguous, complex, or conflicting stimuli is an aversive condition associated with increased levels of arousal. The theory further holds that termination of this condition, through access to relevant information, is rewarding and promotes learning. Despite the importance of curiosity in many aspects of behavior, the topic has been largely neglected in cognitive neuroscience; hence little is known about the neurobiological mechanisms underlying curiosity. To address this issue, we investigated the neural underpinnings of human curiosity using functional magnetic resonance imaging (fMRI).

Because of its many different facets, curiosity has proven difficult to define. To acknowledge the multifaceted nature of curiosity, a two-dimensional categorization of different types of curiosity has been proposed. The first dimension distinguishes between *perceptual* and *epistemic* curiosity. Perceptual curiosity is aroused by novel, strange or ambiguous stimuli, whereas epistemic curiosity refers to the desire for knowledge or intellectual information which applies mainly to humans (Berlyne, 1954). A second, orthogonal, distinction was made between *specific* and *diversive* curiosity, referring to the desire for a particular piece of information versus the more general stimulation-seeking motive that is closely related to boredom (Berlyne, 1960; see Litman, 2008, for a related distinction].

Berlyne proposed that specific curiosity results from *subjective uncertainty*, which is regarded as a form of conflict due to competing hypotheses regarding the object of uncertainty. The concept of subjective uncertainty is analogous to the information-theoretic notion of *entropy H*, which refers to the objective uncertainty of an outcome (Shannon, 1948). Entropy is defined as

$$H(X) = -\sum_{i}^{N} P(x_i) \log_2 P(x_i)$$

, where N is the total number of possible outcomes and $P(x_i)$ is the probability of outcome x_i. Entropy thus increases with the number of possible outcomes and with the nearness in likelihood of the different possible outcomes. Similarly, Berlyne proposed that someone's subjective uncertainty about a specific stimulus or event (e.g., the identity of an object or the solution to a problem) depends on the number of alternative hypotheses he or she has, and the relative confidence placed in each hypothesis.

In the present study, we focused on specific perceptual curiosity, one of the most basic types of curiosity that is found in animals as well as humans. One way to induce specific perceptual curiosity is to present participants with blurred pictures. An early study using this method showed

that blurred pictures evoked longer EEG desynchronization (alpha-wave blocking) than clear pictures, but only when the identity of the blurred pictures was unknown, which provides preliminary evidence that perceptual curiosity causes an increase in arousal (Berlyne & Borsa, 1968). Another experiment showed that the subjective uncertainty induced by a picture, derived from the number of guesses participants made regarding the picture's identity and the relative confidence they placed in each guess, was highest for pictures with an intermediate degree of blur (Nicki, 1970). This study also showed that participants actively preferred to view the clear version of a preceding blurred picture over viewing an unrelated clear picture, and that the preference for uncertainty reduction was strongest for pictures with an intermediate degree of blur (i.e. pictures associated with maximal subjective uncertainty). Importantly, the preference for uncertainty reduction disappeared when participants knew the identity of the blurred picture. These findings are consistent with the idea that the reduction of perceptual curiosity is rewarding.

We used a modified version of the blurred-pictures paradigm to investigate the neural underpinnings of both the induction and the subsequent relief of human perceptual curiosity. More specifically, we examined whether we could find support at the neural level for the main assumptions of Berlyne's classic curiosity theory. First, the assumption that curiosity is an aversive condition of increased arousal predicts that the induction of curiosity will produce activation in brain areas sensitive to autonomic arousal, conflict and other aversive states. Second, the assumption that the reduction of curiosity is rewarding predicts that this will produce activation in brain regions involved in reward processing, such as the striatum. Third, the assumption that the reduction of curiosity promotes learning and memory predicts that uncertainty-reducing stimuli will be associated with enhanced memory performance and related increased hippocampal activation.

We scanned 19 healthy participants while they viewed sequences of two pictures, in a passive-viewing task. To manipulate the induction and reduction of perceptual uncertainty, we used the following four combinations of clear and blurred pictures (Figure 1):

(1) A blurred picture followed by its corresponding clear picture (B-$C_{corresponding}$)

(2) A blurred picture followed by an unrelated clear picture (B-$C_{unrelated}$)

(3) A clear picture followed by an identical picture (C-C)

(4) A clear picture followed by its corresponding blurred picture (C-B)

This design resulted in the induction of perceptual uncertainty by the first picture on half of the trials (the B-$C_{corresponding}$ and B-$C_{unrelated}$ conditions), which was resolved by the second picture on half of these trials (the B-$C_{corresponding}$ condition). We used an intermediate degree of blur for all blurred pictures, because this caused maximal subjective uncertainty (Nicki, 1970). Participants' ratings after the scanning session indicated that they had indeed been curious about the blurred pictures (Supplementary Table 1).

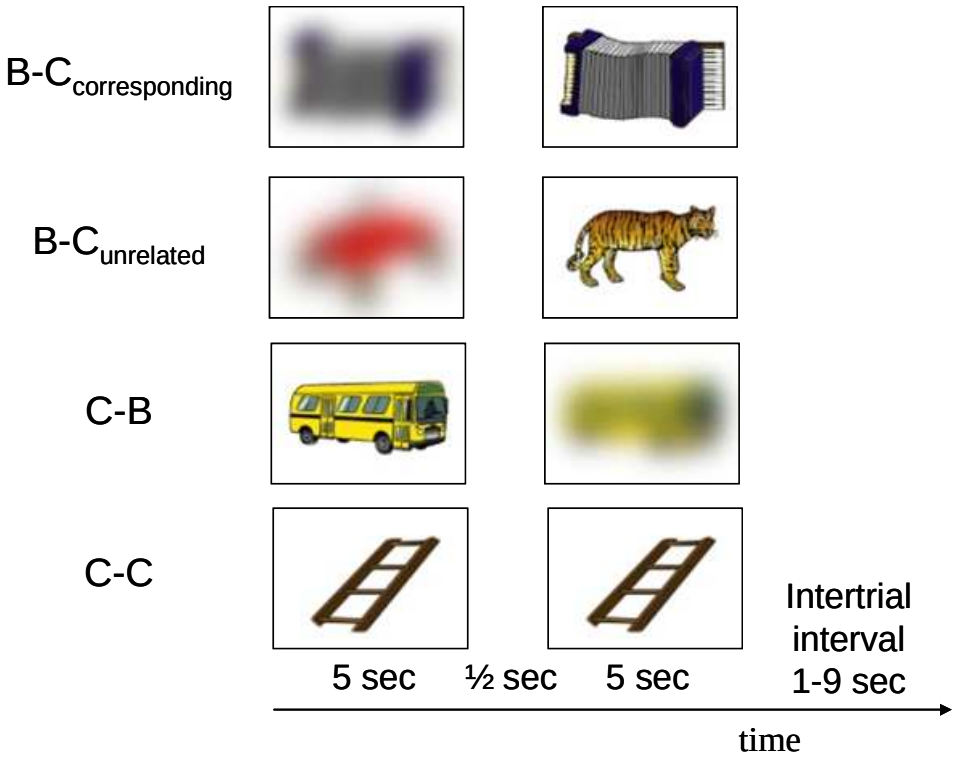

Figure 1. Examples of pictures presented in each of the four conditions. The experiment consisted of 35 trials from each condition, presented in pseudorandom order. Participants were not aware of the aim of the study; we told them that we were interested in the brain activation associated with the perceptual processing of clear and blurred pictures. After scanning, participants were surprised with an unexpected memory test in which they were asked to recall as many objects as possible from the pictures they had seen in the scanner. They also rated several statements regarding their curiosity about the blurred pictures (Supplementary Table 1), and completed the perceptual-curiosity scale [Collins, Litman, & Spielberger, 2004].

Results

Free-recall performance

The number of pictures that participants recalled in an unexpected free-recall test after the scan session was significantly affected by the condition in which the pictures had been presented [$F(3,54) = 11.5$, $p < 0.001$]. Participants recalled more pictures from the B-$C_{corresponding}$ condition (mean = 10.4) than pictures from the B-$C_{unrelated}$, C-C and C-B conditions (mean = 6.1, 7.3 and 8.0, respectively; all ps < 0.03). Thus, incidental memory for uncertainty-reducing stimuli was enhanced.

Brain activation associated with perceptual uncertainty

To examine the brain activation associated with perceptual uncertainty we focused on the neural response to the first picture in each trial, and identified brain regions where activation was larger when the picture was blurred compared to clear. These regions included the bilateral anterior insular cortex (AIC) and anterior cingulate cortex (ACC; Figure 2, upper panel; see Supplementary Table 2 for all activations). Functional-connectivity studies have suggested that the AIC and AAC

are part of a putative “salience network” (Seeley et al., 2007), which has been associated with autonomic arousal (Critchley, 2005) and various aversive emotional experiences (e.g., Craig, Reiman, Evans, & Bushnell, 1996; Eisenberger, Lieberman, & Williams, 2003; Ploghaus, et al., 1999). The idea that the AIC and AAC activations are part of the same functional network was supported in our data by strong across-subject correlations between the strength of the activations in these areas (*p*s < 0.001).

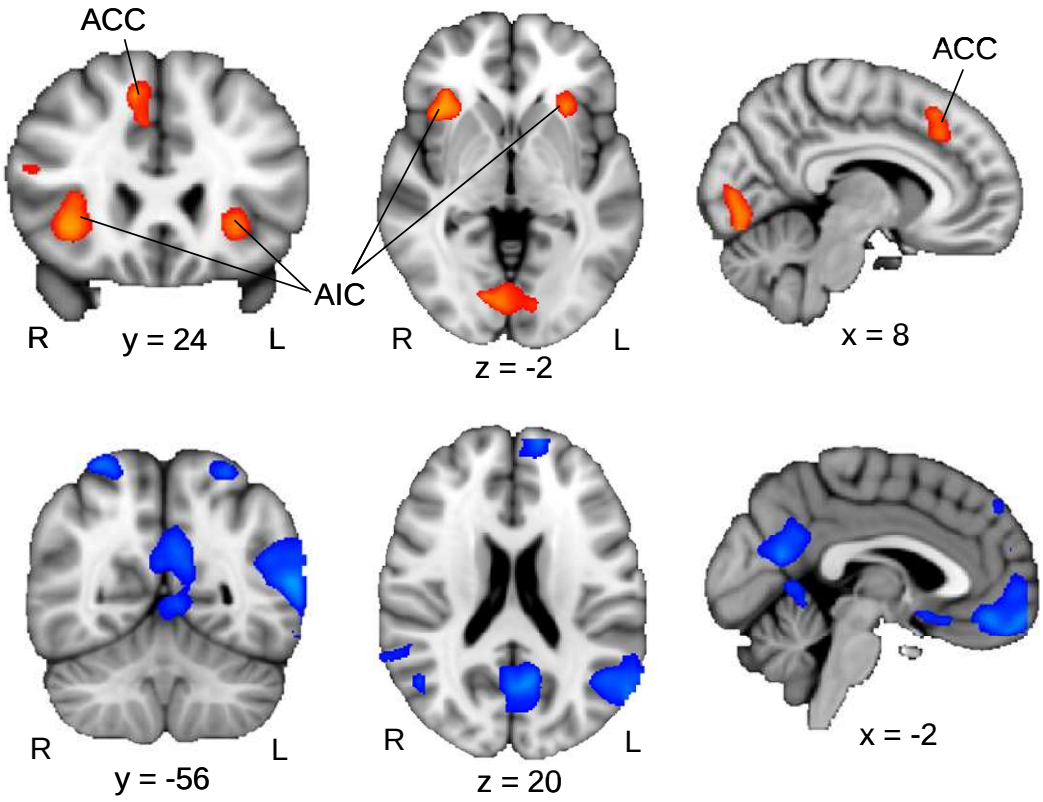

Figure 2. Brain activation associated with perceptual uncertainty.
Upper panel: The colored regions were more active when the first picture in a trial was blurred (i.e. the first pictures in the B-$C_{corresponding}$ and B-$C_{unrelated}$ conditions) than when it was clear (i.e. the first pictures in the C-C and C-B conditions). R = right; L = left; ACC = anterior cingulate cortex; AIC = anterior insular cortex. See also Supplementary Table 2.
Lower panel: The colored regions were deactivated when the first picture in a trial was blurred compared to when it was clear. All displayed activations are whole-brain uncorrected *Z* statistic maps ($p < 0.001$), which were overlaid onto the standard MNI brain.

The opposite contrast, which identified brain regions that were more activated by clear pictures than by blurred pictures, revealed activation in a set of brain regions that have been associated with the ‘default-mode network’ (Figure 2, lower panel). The default-mode network, which includes regions of the precuneus, posterior lateral parieto-occipital cortex and medial prefrontal cortex, is typically stronger activated during rest than during cognitive effort (e.g., Raichle, et al., 2001). The relative deactivation of this network in response to blurred compared to clear pictures suggests that participants actively processed the blurred pictures. Consistent with this

interpretation, participants indicated that they had been curious about the blurred pictures, had tried to guess the identities of the objects depicted in them, and had been rather disappointed when a blurred picture was not followed by its corresponding clear version (Supplementary Table 1).

Several findings suggest that the AIC activation reflected a neural substrate of a negative arousal state associated with perceptual curiosity. First, the activated regions of the AIC closely overlap with areas that are typically activated in response to errors, negative feedback and other aversive events (Ullsperger, Harsay, Wessel, & Ridderinkhof, 2010). Second, the strength of participants' AIC activation was positively correlated with their trait curiosity as indexed by the perceptual-curiosity questionnaire (r = 0.52, p = 0.02 and r = 0.46, p = 0.049 for the right and left AIC, respectively; Figure 3). Third, the participants who reported more disappointment when the identity of a blurred picture was not revealed showed stronger left AIC activation than the participants who reported less disappointment [$t(17)$ = 2.0, p(1-tailed) = 0.03; see Materials and Methods].

Interestingly, the strength of participants' AIC and ACC activation associated with perceptual uncertainty was predictive of the number of pictures they later recalled from the B-$C_{corresponding}$ condition (r = 0.46, p = 0.048 and r = 0.59, p = 0.008 for the right AIC and ACC, respectively; the correlation with the left AIC was marginally significant), but not of the number of pictures they recalled from the other conditions (all ps > 0.3). This suggests that the uncertainty-related activation of the AIC and ACC contributed to the enhanced memory for stimuli that reduced this uncertainty.

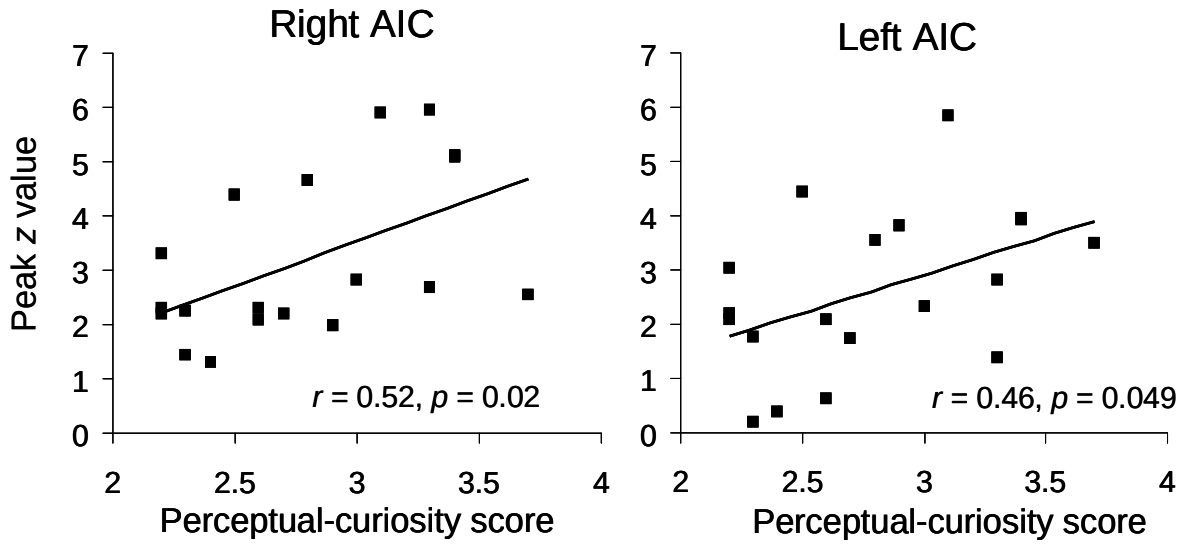

Figure 3. The individual participants' peak activation (z value) for the perceptual-uncertainty contrast in the right and left AIC plotted against their perceptual-curiosity score.

Brain activation associated with the relief of perceptual uncertainty

To examine the brain activation associated with the relief of perceptual uncertainty, we created a contrast that identified brain regions where activation was larger in response to the second picture in the B-$C_{corresponding}$ condition than in response to the second picture in the B-$C_{unrelated}$

condition. Significant activation was found in regions of the dorsal striatum (the left caudate and right putamen), and in the left lateral orbitofrontal cortex extending into the ventral striatum (ventral putamen; Figure 4; see Supplementary Table 3 for all activations). Striatal activation has been associated with reward processing, the coding of 'reward-prediction errors' (i.e., the difference between observed and expected reward) and reinforcement learning (Daw & Doya, 2006; Haruno & Kawato, 2006; O'Doherty, 2004). Since the uncertainty induced by a blurred picture was relieved by the following picture on only half of the trials, the reduction of perceptual uncertainty by the second picture possibly caused a (partial) reward-prediction error. Accordingly, the striatal activation could reflect the reward value and/or the reward-prediction error associated with the relief of perceptual uncertainty.

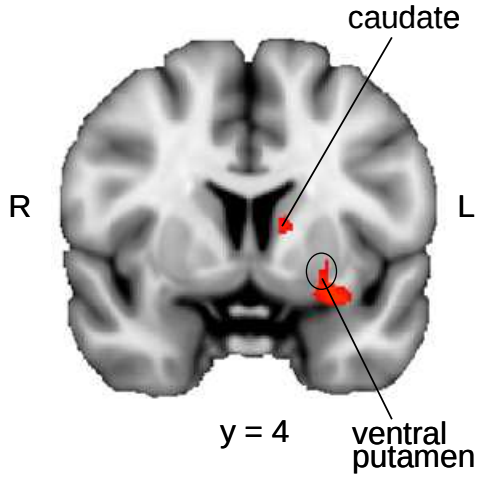

Figure 4. Brain activation associated with the reduction of perceptual uncertainty. The colored regions were more active when the second picture in a trial reduced the perceptual uncertainty induced by the preceding picture (i.e., the second picture in the B-$C_{corresponding}$ condition) than when the second picture did not reduce the perceptual uncertainty induced by the preceding picture (i.e., the second picture in the B-$C_{unrelated}$ condition). R = right; L = left. The displayed activations are whole-brain uncorrected *Z* statistic maps ($p < 0.001$), which were overlaid onto the standard MNI brain. See also Supplementary Table 3.

Confirming predictions, a region-of-interest (ROI) analysis of the hippocampus revealed that regions of the bilateral hippocampus showed stronger activation in response to the second picture in the B-$C_{corresponding}$ than in the B-$C_{unrelated}$ condition (Figure 5). A contrast that identified brain regions where activation was larger in response to the second picture in the B-$C_{corresponding}$ condition than in the C-C condition also revealed significant activation in the left hippocampus (360 mm^3 at $p < 0.001$, uncorrected). The event-related time courses of the BOLD signal in response to the second picture in each of the four conditions illustrate the specific increase in hippocampal activation for the B-$C_{corresponding}$ condition (Figure 5). The increased hippocampal activation in response to uncertainty-reducing stimuli likely underlied the enhanced later recall of these stimuli. Interestingly, the strength of participants' hippocampal activation in response to the reduction of uncertainty was positively correlated with the strength of their right-AIC activation in response to

the induction of uncertainty (r = 0.57, p = 0.01 and r = 0.47, p = 0.04 for the left and the right hippocampal ROI, respectively). In addition, there was a positive correlation between the strength of the hippocampal activation and the right putamen activation (r = 0.48, p = 0.04 for both hippocampal ROIs). This is consistent with the recent hypothesis that interactions between the hippocampus and midbrain dopamine neurons and their striatal targets promote memory for rewarding or otherwise motivationally significant events (Shohamy & Adcock, 2010).

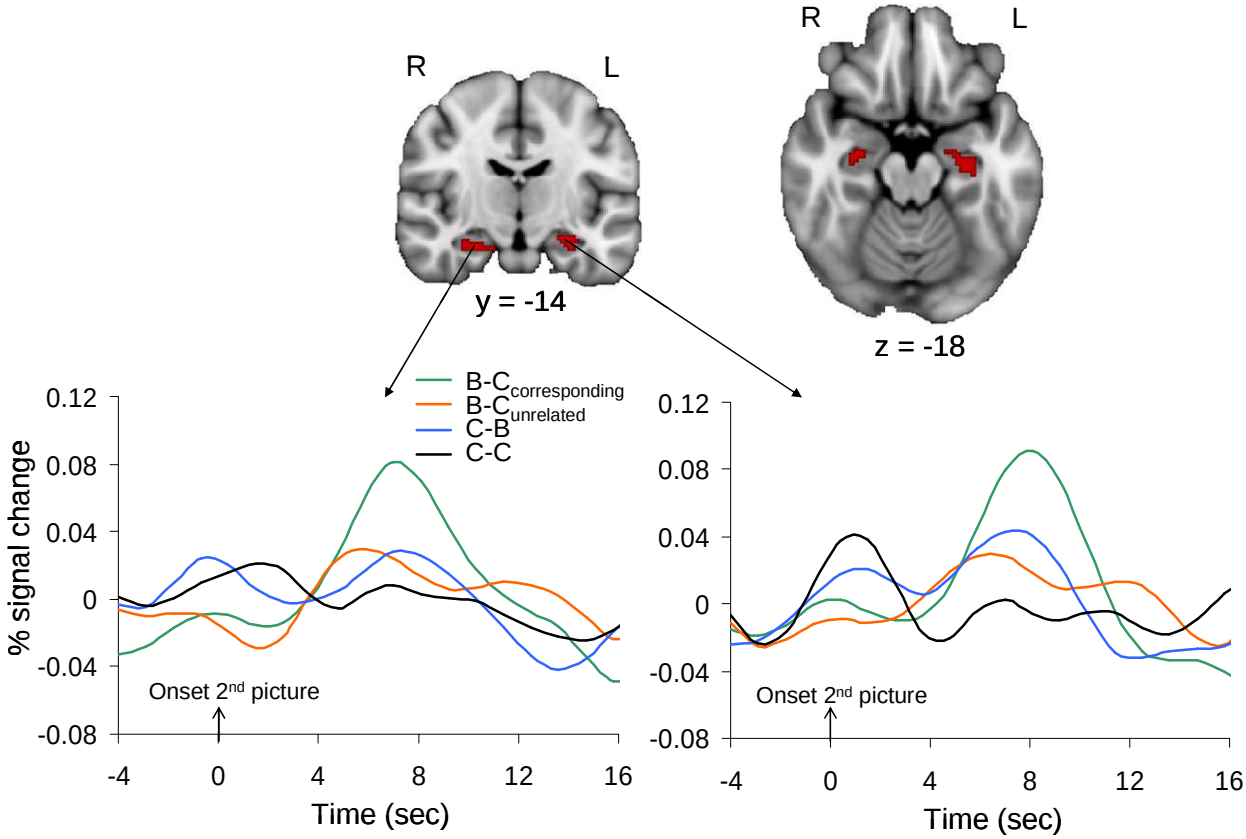

Figure 5. Hippocampal activation associated with the reduction of perceptual uncertainty.
Upper panel: The colored regions were more active when the second picture in a trial reduced the perceptual uncertainty induced by the preceding picture (i.e., the second picture in the B-$C_{corresponding}$ condition) than when the second picture did not reduce the perceptual uncertainty induced by the preceding picture (i.e., the second picture in the B-$C_{unrelated}$ condition). The displayed activations are the uncorrected Z statistic maps in the hippocampal ROIs (p < 0.01) overlaid onto the standard MNI brain.
Lower panel: Time course of of hemodynamic activity in response to the second picture in each of the four conditions. Time courses were extracted from the hippocampal activation clusters shown in the upper panel.

Discussion

The present study is the first demonstration of the neurobiological basis of human perceptual curiosity. By elucidating the neural underpinnings of the induction and relief of perceptual curiosity, our study extends existing behavioral accounts of curiosity. In particular, our results provide compelling neurobiological evidence for Berlyne's classic psychological theory of curiosity

(Berlyne, 1954, 1960, 1966). First, our finding that perceptual uncertainty activated brain regions sensitive to arousal and conflict supports the assumption that curiosity evoked by ambiguous stimuli is an aversive condition, and induces an increase in arousal. Second, our finding that the reduction of perceptual uncertainty activated brain regions involved in reward processing supports the assumption that the termination of this condition, through access to relevant information, is rewarding. Third, our findings that the reduction of perceptual uncertainty was associated with increased hippocampal activation and enhanced incidental memory support the assumption that uncertainty reduction facilitates memory and learning.

Our findings are also consistent with Loewenstein's information-gap account of curiosity which proposes that curiosity is a negative feeling of deprivation that is caused by an inconsistency, or gap, between one's actual and aspired level of knowledge (Loewenstein, 1994). Since people differ in their aspired level of knowledge, the same actual level of knowledge will evoke curiosity in some people but not in others. In line with this idea, we found that inter-individual variation in trait perceptual curiosity correlated with the strength of AIC activation in response to perceptual uncertainty, suggesting that people with a higher level of aspired perceptual knowledge experience stronger negative feelings when confronted with ambiguous perceptual input.

We found that perceptual curiosity was associated with activation in the AIC and the ACC, regions of a putative salience network that is sensitive to conflict and arousal. These activations may have been modulated by the neuromodulatory locus coeruleus-norepinephrine (LC-NE) system. The LC exhibits strong activity at times of elevated arousal and exhibits a phasic increase in activity in response to motivationally significant stimuli (Aston-Jones & Cohen, 2005). The ensuing release of NE leads to an increased responsivity of neurons in LC projection areas, including the ACC and AIC (Berridge & Waterhouse, 2003). Thus, the activation of these brain regions in response to curiosity-inducing stimuli was possibly driven by an increased noradrenergic innervation. Consistent with this idea, pharmacological studies in rats have shown that behavioral exploration of novel or unexpected objects is mediated by the LC-NE system (Devauges & Sara, 1990; Mansour, et al., 2003; Sara, Dyon-Laurent, & Hervé, 1995).

The relief of perceptual curiosity was associated with activation in regions of the striatum that are involved in reward processing, suggesting that curiosity reduction is rewarding. This idea is consistent with previous behavioral findings that people actively prefer to view the clear version of a preceding blurred picture over viewing an unrelated clear picture (Nicki, 1970). Other work has shown that people have a similar preference for exploring perceptually novel over familiar stimuli, a tendency that is also associated with striatal activation (Wittmann, Daw, Seymour, & Dolan, 2008). In the reinforcement-learning literature, this bias towards the exploration of uncertain or novel options is captured by the concept of an "exploration bonus" that is assigned to uncertain or novel stimuli to promote their exploration (Kakade & Dayan, 2002).

The relief of perceptual curiosity was also associated with enhanced incidental memory, and with increased hippocampal activation, a plausible neural substrate underlying the behavioral memory effect. Furthermore, there was a positive across-subject correlation between the strength of

the hippocampal and putamen activations in response to uncertainty reduction, suggesting that interactions between these areas contributed to the enhanced memory for curiosity-reducing stimuli. The finding that curiosity reduction leads to enhanced memory suggests that the induction of curiosity before the presentation of teaching material (e.g., by asking people to guess the meaning of foreign words before showing them the translations) can facilitate learning.

Although no prior studies have investigated the neural mechanisms underlying perceptual curiosity, one recent study has investigated the neural substrates of specific epistemic curiosity evoked by the presentation of trivia questions (Kang, et al., 2009). That study found that questions that were rated as more puzzling were associated with stronger activation in regions of the caudate. However, since the questions were always followed by their correct answers, it was unclear whether this activation reflected epistemic curiosity, feedback anticipation, or a combination of the two. In our study, the curiosity induced by blurred pictures was often not relieved, which allowed examination of the neural correlates of pure curiosity. In addition, by comparing conditions in which the second picture did versus did not reduce perceptual uncertainty, we could separately examine the neural correlates of the relief of curiosity.

We did not ask participants to rate their curiosity on each trial since we were concerned that this would confound the brain activation reflecting their natural curiosity. Therefore, a limitation of our study is that we could not take into account trial-to-trial variation in experienced curiosity. In addition, it is likely that curiosity reduction through passive exposure to uncertainty-reducing stimuli, as examined in the present study, differs from curiosity reduction that is achieved through active exploration. A recent study showed that hippocampus activation was stronger when people had volitional control over the visual exploration of pictures in a visual-learning task than when they received exactly the same visual information in a passive condition (Voss, Gonsalves, Federmeier, Tranel, & Cohen, 2011). This suggests that the hippocampus activation associated with uncertainty reduction that we found in the present study would have been even stronger if participants would have had the opportunity to actively control the exploration of uncertainty-inducing stimuli.

To conclude, our results provide evidence at the neural level that perceptual curiosity evokes an aversive state of increased arousal, whose termination is rewarding and promotes incidental memory. Because curiosity plays a key role in many aspects of human behavior, a better understanding of the psychological and neurobiological basis of curiosity may have considerable practical implications for various societal objectives. Together with previous behavioral findings (Berlyne & Normore, 1972), our results suggest that inventing ways to arouse people's curiosity could contribute to the optimization of educational systems and advertising strategies, and may promote scientific discovery.

Materials and methods

Participants

Nineteen healthy volunteers participated (14 women and 5 men; aged 19–29 years; mean age = 22.8 years; SD = 2.4), in return for €25,-. Participants gave written consent before participation, and the study was approved by the medical ethics committee of the Leiden University Medical Center. All participants had normal or corrected-to-normal vision and reported to be right-handed.

Stimuli and procedure

The stimuli used in the task were pictures of common objects selected from Rossion and Pourtois' colored picture databank (Rossion & Pourtois, 2004). This databank is a set of 260 colored line drawings of objects, provided with norms for name agreement, image agreement, familiarity, and complexity ratings. We selected 140 pictures with perfect name agreement from this databank. All pictures had a resolution of 71 dpi, and were centered on a white rectangle of 197 x 281 pixels. We created a blurred version of each picture by means of Gaussian smoothing with a radius of 20 to 22 pixels (Adobe Photoshop 5.0; all pictures can be found at www.sandernieuwenhuis.nl/SOM). By reducing the picture's high-frequency components, Gaussian smoothing acts as a low-pass filter. Results from a behavioral pilot experiment with 49 participants indicated that the objects displayed in the blurred pictures could not be identified by the majority of the participants.

On each trial, a sequence of two pictures was presented. The pictures were projected onto a screen and viewed through a mirror attached to the head coil of the scanner. Each picture was presented for 5 s in the middle of the screen on a white background, and was surrounded by a black frame (18.5 x 13.8°). The two pictures in a trial were separated by a 500-ms interval during which only the frame was presented. The intertrial interval varied between 1 and 9 s (uniform distribution).

The experiment consisted of 35 trials from each of four conditions illustrated in Figure 1, presented in pseudorandom order. For the blurred pictures in the B-$C_{unrelated}$ condition we used blurred versions of 35 additional pictures from Rossion and Pourtois' databank (i.e. pictures of which the clear version was not used). The 140 clear pictures were presented in the same order for all participants. To exclude the possibility that differences between the conditions were caused by picture-specific effects, we divided the 140 clear pictures into four subsets of 35 pictures with comparable familiarity, complexity and imagery ratings (all *p*s > 0.86) and alternated the coupling of the four picture subsets to the four conditions across participants according to a balanced Latin-square design.

The experiment was divided into five runs of 28 trials between which we stopped the scanner and talked with the participant to verify that he or she was still attending to the pictures. Each run contained seven trials from each condition and lasted approximately eight minutes. We

told the participants that the experiment was designed to investigate the brain activation associated with the perceptual processing of clear and blurred pictures, and informed them of the four possible ways in which clear and blurred pictures could be combined.

After completing the experiment, participants were given an unexpected free-recall test outside the scanner; they were asked to type in the names of as many objects as they could recall from the pictures they had seen in the scanner. Subsequently, participants were asked to indicate, on a 5-point scale (1 = not at all; 5 = very much), the degree to which they had (1) been curious about the blurred pictures; (2) tried to guess the identity of the objects depicted on the blurred pictures; (3) been disappointed when a blurred picture was not followed by the corresponding clear version; (4) recognized the objects depicted on the blurred pictures; and (5) tried to remember the pictures. Finally, participants completed the perceptual curiosity scale (Collins, Litman, & Spielberger, 2004).

Image acquisition

Scanning was performed with a standard whole-head coil on a 3-T Philips Achieva MRI system (Best, The Netherlands). In each of the five functional runs, 210 T2*-weighted whole-brain EPIs were acquired (TR = 2.2 sec; TE = 30 ms, flip angle = 80°, 38 axial slices, 2.75 x 2.75 x 2.75 mm + 10% interslice gap). In addition, a high-resolution EPI scan and a T1-weighted anatomical scan were obtained for registration purposes (EPI scan: TR = 2.2 ms; TE = 30 ms, flip angle = 80°, 84 axial slices, 1.96 x 1.96 x 2 mm; 3D T1-weighted scan: TR = 9.7 ms; TE = 4.6 ms, flip angle = 8°, 140 axial slices, 0.88 x 0.88 x 1.2 mm).

Image analysis

MRI data analysis was carried out using FEAT (FMRI Expert Analysis Tool) version 5.98, which is part of FSL (FMRIB's Software Library; Smith et al., 2004). Image pre-processing consisted of motion correction (Jenkinson, Bannister, Brady, & Smith, 2002), non-brain removal (Smith, 2002), spatial smoothing using a Gaussian kernel of FWHM 8.0 mm, grand-mean intensity normalization of the entire 4D data set by a single multiplicative factor, and high-pass temporal filtering to remove low-frequency artifacts (Gaussian-weighted least-squares straight line fitting, with sigma = 100 s). Functional scans were registered to high-resolution EPI images, which were registered to T1 images, which were registered to standard MNI space (Jenkinson, et al., 2002; Jenkinson & Smith, 2001).

The fMRI time series were analyzed using an event-related approach in the context of a general linear model with local autocorrelation correction (Woolrich, Ripley, Brady, & Smith, 2001). We constructed six explanatory variables of interest: two for the first picture in a trial (Blurred or Clear), and four for the second picture in a trial (Clear-corresponding, Clear-unrelated, Clear-double, or Blurred). Each explanatory variable was time-locked to the picture onset and had a duration of 5 s (i.e., the entire duration of the picture presentation). The hemodynamic response to each event was estimated by convolving each explanatory variable with a canonical hemodynamic

response function and its temporal derivative. The model was high-pass-filtered (Gaussian-weighted least-squares straight line fitting, sigma = 100 s).

For each run, in each participant, we assessed several contrasts. The contrasts were combined across the five runs on a subject-by-subject basis using fixed-effects analyses (Beckmann, Jenkinson, & Smith, 2003; Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004). These second-level contrast images were submitted to third-level mixed-effects whole-brain group analyses (Beckmann et al., 2003; Woolrich et al., 2004). The statistical parametric images were thresholded at $p < .001$ (uncorrected), in combination with a minimum cluster size of 200 mm^3.

Region-of-interest analyses. In addition to the whole-brain analyses, we conducted region-of-interests (ROI) analyses to test the predicted hippocampus activation in response to the relief of perceptual uncertainty. We used anatomical ROIs of the left and right hippocampus specified by the Harvard–Oxford subcortical structural atlas, as implemented in FSLView version 3.1.2. Only the voxels that were part of the hippocampus with a probability of at least 50% were included in the ROIs, resulting in left and right hippocampus ROIs of 4016 and 4248 mm^3, respectively. We tested for activation within these ROIs that exceeded an uncorrected threshold of $p < 0.01$. To further examine the hippocampal activation, we extracted the average time course of the hemodynamic response function in response to the second picture in each of the four conditions using PEATE (perl event-related average time course extraction), a companion tool to FSL (http://www.jonaskaplan.com/peate/peate-tk.html). Time courses were extracted from the hippocampal activation clusters of the curiosity-relief contrast (i.e., the regions with stronger activation in response to the second picture in the B-$C_{corresponding}$ condition than in response to the second picture in the B-$C_{unrelated}$ condition).

To examine whether individual differences in trait-perceptual curiosity and free-recall performance were predictive of individual differences in brain activation, we extracted each participant's peak *z* value from the activation clusters of interest (the AIC and ACC activations for the perceptual-uncertainty contrast, and the caudate, putamen and hippocampus clusters for the uncertainty-reduction contrast). We correlated these peak *z* values with participants' scores on the perceptual-curiosity questionnaire and with their free-recall performance. In addition, we computed the across-subject correlations between the peak *z* values of the different activation clusters of interest.

Disappointment median-split analysis. To examine whether participants' rated disappointment when the identity of a blurred object was not revealed predicted the strength of their AIC activation in response to perceptual uncertainty, we divided all participants into two groups based on their disappointment ratings: nine participants reported a strong disappointment (ratings of 4 or 5 on a five-point scale) and the other ten participants reported less disappointment (ratings of 2 or 3). We used a *t*-test to determine whether the high-disappointment group showed stronger AIC activation in response to perceptual uncertainty than the low-disappointment group.

Appendix

Supplementary Table 1. Participants' ratings of the degree to which they had been curious about the blurred pictures, recognized the blurred pictures, and had tried to remember the pictures (means ± standard deviations). All ratings were on a scale from 1 (not at all) to 5 (very much).

I was curious about the blurred pictures	4.11 ± 0.88
I tried to guess the identity of the objects depicted in the blurred pictures	4.53 ± 0.70
I was disappointed when a blurred picture was not followed by its clear version	3.16 ± 1.02
I recognized the objects depicted in the blurred pictures	2.79 ± 0.92
I tried to remember the pictures	1.74 ± 0.73

Supplementary Table 2. Regions showing stronger activation when the first picture in a trial was blurred compared to clear. Data are thresholded at $p < 0.001$, uncorrected, and only clusters exceeding 200 mm^3 are reported.

Region	Left/Right	Cluster size (mm^3)	Z_{MAX}	MNI peak coordinates (mm)		
				x	y	z
Anterior insular cortex	R	3192	4.32	36	24	-4
Anterior insular cortex	L	1152	4.11	-28	22	-4
Anterior cingulate cortex	R	1464	4.13	10	24	48
Anterior cingulate cortex	L	488	3.45	-6	12	44
Inferior frontal gyrus	R	3240	4.00	50	16	26
Frontal pole	R	424	3.51	32	48	8
Lingual gyrus	R/L	5520	4.09	8	-80	-8
Occipital pole	L	912	4.21	-12	-94	10
Posterior cingulate gyrus	R/L	616	3.91	2	-30	24

Supplementary Table 3. Regions showing stronger activation in response to the second picture in the B-$C_{corresponding}$ condition compared to the B-$C_{unrelated}$ condition. Data are thresholded at $p < 0.001$, uncorrected, and only clusters exceeding 200 mm^3 are reported.

Region	Left/Right	Cluster size (mm^3)	Z_{MAX}	MNI peak coordinates (mm)		
				x	y	z
Caudate (dorsal striatum)	L	224	3.26	-12	6	10
Putamen (dorsal striatum)	R	600	3.55	30	-20	10
Orbitofrontal cortex (extending into ventral putamen)	L	624	3.54	-28	6	-12
Lateral occipital cortex	R/L	1808	3.46	40	-74	0
Posterior insula	R	456	3.57	42	-4	6