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A common neural scale for the subjective pleasantness of different primary rewards

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ABSTRACT

When an economic decision is taken, it is between goals with different values, and the values must be on the same scale. Here, we used functional MRI to search for a brain region that represents the subjective pleasantness of two different rewards on the same neural scale. We found activity in the ventral prefrontal cortex that correlated with the subjective pleasantness of two fundamentally different rewards, taste in the mouth and warmth on the hand. The evidence came from two different investigations, a between-group comparison of two independent fMRI studies, and from a within-subject study. In the latter, we showed that neural activity in the same voxels in the ventral prefrontal cortex correlated with the subjective pleasantness of the different rewards. Moreover, the slope and intercept for the regression lines describing the relationship between activations and subjective pleasantness were highly similar for the different rewards. We also provide evidence that the activations did not simply represent multisensory integration or the salience of the rewards. The findings demonstrate the existence of a specific region in the human brain where neural activity scales with the subjective pleasantness of qualitatively different primary rewards. This suggests a principle of brain processing of importance in reward valuation and decision-making.

Introduction

Making adaptive choices between different types of rewards requires a comparison of their values on a common scale. For example, consider a situation where a choice has to be made between consuming a palatable food and approaching a source of warm pleasant touch. In order to decide between these different courses of action the brain needs to compare the values of two fundamentally disparate rewarding outcomes. It has been suggested that the values of different kinds of rewards are converted into a common currency (Montague and Berns, 2002; Rolls, 1999) so as to represent them on the same scale (Rolls and Grabenhorst, 2008). According to economic utility theory (Bernoulli, 1738/1954), individuals represent the desirability of different goods by assigning subjective utilities to them that can be measured in individual choices. Ecological theories (McFarland and Sibly, 1975) also propose that choosing between different courses of action requires a comparison of their subjective values in a common currency.

From a psychological perspective, subjective pleasure may serve as the state that corresponds to this common currency (Cabanac, 1992). This can be measured by subjective ratings given by human subjects. Brain imaging can then be used to identify regional activations that correlate with these ratings. Using this approach, neural representations of the subjective pleasantness of different types of rewards have been found in brain areas including the orbitofrontal (Grabenhorst and Rolls, 2009; Grabenhorst et al., 2007; Grabenhorst et al., 2010; Kringelbach et al., 2003) and anterior cingulate cortices (Grabenhorst and Rolls, 2008; Grabenhorst et al., 2007; Grabenhorst et al., 2010; McCabe and Rolls, 2007). However, none of these investigations has directly tested whether the same brain area represents the subjective pleasantness of qualitatively different rewards on a common neural scale.

Using an operational measure of value inferred from choices it has been shown that single neurons in the macaque orbitofrontal cortex encode an abstract representation of the economic value of juice rewards as a linear function of their firing rate (Padoa-Schioppa and Assad, 2006). This representation is invariant with respect to the different types of juice that are available (Padoa-Schioppa and Assad, 2008).

It remains unclear, however, whether a common brain region also encodes the subjective reward value of qualitatively different types of reward, rather than, for example two types of juice (Padoa-Schioppa and Assad, 2008). A recent functional neuroimaging investigation has shown that the human striatum processes monetary as well as social rewards (Izuma et al., 2008). However, the crucial comparison in that study was between receiving a high reward and receiving no reward, which leaves open the possibility that the effects were related to the salience of receiving an affective stimulus and not reward value per se.

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Moreover, the study did not correlate activations with subjective ratings of value.

In the present experiments, we therefore compared two qualitatively different rewards, and used fMRI to test whether brain areas were present with activations that correlate with the subjective ratings of pleasantness of both the hand thermal and taste/flavor types of reward. We also checked whether the relationship between the activations and ratings of pleasantness was due to salience or intensity.

Materials and methods

Design

We compared two qualitatively different rewards, and used fMRI to search for activations that correlated with the subjective ratings of pleasantness of both types of reward. In Investigation 1 we performed two fMRI studies that separately investigated neural value representations for thermal stimuli applied to the hand and for taste rewards, and then combined these datasets at the group level in order to test whether there were brain areas in which the activations were related to the subjective ratings for both temperature and taste reward.

We found in Investigation 1 common brain areas where activations were related to the pleasantness of both temperature and taste reward. We therefore performed Investigation 2 in which in the single event design thermal stimuli applied to the hand, and flavor stimuli, were interleaved in permuted trial order in individual subjects, allowing us to test again whether common areas were activated by the thermal and flavor reward stimuli, and if so, whether the BOLD (blood oxygenation-level dependent) activations found in relation to the pleasantness of these different stimulus types were on the same scale. The similarity of the scale was tested by comparing the slope of the change of the BOLD signal as a function of the subjective pleasantess ratings of the two types of stimuli. We ensured that the behavior required on the temperature and flavor trials was similar by asking for similar ratings on both trial types, namely ratings of pleasantness and then of intensity/fattiness.

Importantly, we also checked whether the relationship between the activations and ratings of pleasantness was due to salience or intensity. We did this in two ways. First, we included both positive and negative rewards which were more salient than the neutral stimuli. Second, we obtained independent ratings of the intensity or sensory properties of the stimuli. This allowed us to rule out the possibility that the relationship to pleasantness was artefactual.

Subjects

All experiments were with healthy volunteers who gave written informed consent before the experiments. Ethical approval was provided by the Central Oxford Research Ethics Committee. For Investigation 1, twelve healthy volunteers (6 males and 6 females, mean age 26) participated in the study involving temperature stimuli and twelve different healthy volunteers (6 males and 6 females, mean age 24) in the study involving taste stimuli, as previously reported (Grabenhorst et al., 2008a; Rolls et al., 2008a). Fourteen different healthy volunteers (9 males and 5 females, mean age 24) participated in Investigation 2. The participants in the taste study in Investigation 1 and the participants in Investigation 2 were asked not to eat for 3 h before the experiment.

Experimental protocol

For the temperature study reported in Investigation 1, different thermal stimuli were applied to the hand on each trial. The different thermal stimuli were a warm pleasant stimulus (41 °C), a cold unpleasant stimulus (12 °C), a combined warm and cold stimulus (41 °C + 12 °C), and a second combination designed to be less pleasant (39 °C + 12 °C). Two separate thermodes were applied to the palm and dorsum of the hand. This allowed us to produce mixtures of warm and cold simultaneously on a single trial to provide a wider range of affective stimuli. For the taste study reported in Investigation 1, a taste stimulus consisting mainly of 0.1 M monosodium glutamate (MSG) which produced the taste of umami, was delivered orally on each trial and labelled on different trials as 'rich and delicious taste' or 'monosodium glutamate'. The word labels were designed to modulate the subjective pleasantness of the taste stimulus. Because the subjects made ratings of the pleasantness and intensity of the stimuli in both investigations, we were able to analyze how their subjective evaluation of the thermal and taste stimuli in terms of their pleasantness and intensity were related to neural activations in different brain regions by correlating the subjective ratings with the fMRI BOLD signals measured on every trial. In both investigations, the participants were instructed to spread their ratings of pleasantness throughout the range of the rating scale, and the participants had experienced the full range of the different stimuli before the start of the experiment. The analyses conducted for Investigation 1 were based on datasets collected for previous investigations of the neural correlates of the reward value of temperature and taste stimuli (Grabenhorst et al., 2008a; Rolls et al., 2008a). Details on the experimental design and functional imaging acquisition and analysis used in these investigations are provided in the Supplementary methods.

For Investigation 2, different thermal and flavor stimuli were delivered on each trial. The thermal stimuli were applied to the hand and consisted of a warm pleasant stimulus (38 °C) or a cold unpleasant stimulus (14 °C). The ambient room temperature was approximately 20 °C for all subjects. To allow for individual differences in sensitivity to thermal stimuli the thermal stimuli were adjusted by up to 1 °C for each participant before the scanning so that the warm stimulus was rated as pleasant and the cold stimulus as unpleasant without being painful. The flavor stimuli consisted of a pleasant vanilla-flavored dairy drink and, to provide for a range of pleasantness values in the investigation, an unpleasant strawberry-flavored dairy drink. Both types of flavor stimuli were presented as a low fat version (0.1% fat milk) and a high fat version (single cream, 18% fat) to produce a range of liquid food stimuli that differed in taste, olfactory and texture components. For example, the vanilla and strawberry stimuli differed in their amount of sweetness (a primary taste quality) and their retronasal olfactory component (vanilla vs. strawberry odor), and it is these differences that define the flavor of the stimuli. The instructions given to the subjects stated that they should rate the pleasantness of the flavor of the liquid food stimuli. Flavor was defined in the instructions as a combination of taste and smell components and the subjects were instructed to rate the overall pleasantness of these effects independently of the fattiness or texture of the stimuli. The drinks were made by taking either single cream or the low fat milk as the base, and the flavor component was specified by vanilla food flavor and 5 g/100 ml (0.15 M) sucrose, or by strawberry food flavor without sucrose. We also included a neutral temperature stimulus and a tasteless control solution which were delivered at the end of each trial. The neutral temperature stimulus was produced by neither cooling nor warming the thermode. The tasteless rinse and control solution contained the main ionic components of saliva (25 mM KCl + 2.5 mM $NaHCO_3$) which when subtracted from the effects produced by the taste stimulus allowed somatosensory and any mouth movement effects to be distinguished from the effects purely related to taste (de Araujo et al., 2003a,b). This is an important control condition that we have pioneered to allow taste areas to be shown independently of any somatosensory effects produced by introducing a fluid into the mouth (de Araujo et al., 2003a,b). Controlled thermal stimuli were applied using an adapted commercially available Peltier thermode (MEDOC, Haifa, Israel; 30 × 30 mm thermo-conducting surface) strapped to the dorsum of the left hand. The method of stimulus delivery ensured that the

devices were continually in place during the experiment, and that only temperature changes were occurring in the stimulation periods with no adjustment or movement of the thermode that might produce somatosensory stimulation being possible in the whole experiment. In the preliminary testing, the exact temperatures used for each subject were tailored ±2 °C, so that the warm stimulus was rated as pleasant and the cold stimulus as unpleasant but not painful. Flavor stimuli were delivered to the subject's mouth through teflon tubes (one for each of the 4 flavor stimuli, and a separate tube for the tasteless rinse control) that were held between the lips. Each teflon tube of approximately 3 m in length was connected to a separate reservoir via a syringe and a one-way syringe activated check valve (Model 14044-5, World Precision Instruments, Inc.) that allowed 0.75 ml of any stimulus to be delivered at the time indicated by the computer.

For Investigation 2 each trial started with a visual cue displayed for 1 s to indicate to the subjects whether the current trial was a temperature ("T") or flavor ("F") trial. Following the visual cue, a temperature or flavor stimulus, chosen by random permutation, was delivered accompanied by a visual cue to indicate the stimulus delivery. Then at 7 s after stimulus delivery, a visual cue presented for 2 s indicated the end of the stimulus period on both temperature and flavor trials and also cued the participants to swallow on the flavor trials (following initial instruction and training). After this period, ratings were made with visual analogue rating scales in which the participant moved a bar to the appropriate point on the continuous scale using a button box. Subjects rated the temperature stimuli for pleasantness (with +2 being very pleasant and −2 very unpleasant) and intensity (with 0 being very weak and 4 very strong), and the flavor stimuli for pleasantness of flavor and texture (with +2 being very pleasant and −2 very unpleasant), and for fattiness (0 to +4). The subjects were instructed to rate the intensity and the fattiness of the stimuli independently of how pleasant the stimuli were. Each rating period was 4 s long. Participants were pre-trained in the use of the rating scales. After the last rating a small visual cue indicated the delivery of the neutral temperature stimulus or the tasteless control solution which were administered in exactly the same way as the test stimuli. Termination of the control stimulus period after 7 s as well as the swallowing period on the flavor trials were cued by a visual stimulus. On the flavor trials, the instruction given to the participant was to move the tongue once as soon as a stimulus or tasteless solution was delivered (at the time when a visual stimulus was turned on) in order to distribute the solution round the mouth to activate the receptors for taste and smell, and then to keep still for the remainder of the 7 s until a cue indicated when the participant could swallow. There was then a 4 second delay period before the next trial started. Each experimental stimulus was presented in permuted sequence 12 times. This general protocol and design have been used successfully in previous studies to investigate activations and their relation to subjective ratings in cortical areas (de Araujo et al., 2005; Grabenhorst and Rolls, 2009; Grabenhorst et al., 2007; Grabenhorst et al., 2010; Rolls et al., 2003a).

Functional imaging data: acquisition

Images were acquired with a 3.0-T Varian-Siemens whole-body scanner at the Centre for Functional Magnetic Resonance Imaging at Oxford (FMRIB), where 27 T2* weighted EPI coronal slices with in-plane resolution of 3×3 mm and between plane spacing of 4 mm were acquired every 2 s (TR = 2). We used the techniques that we have developed over a number of years (de Araujo et al., 2003a) and as described in detail by Wilson et al. (2002) we carefully selected the imaging parameters in order to minimize susceptibility and distortion artefact in the orbitofrontal cortex. The relevant factors include imaging in the coronal plane, minimizing voxel size in the plane of the imaging, as high a gradient switching frequency as possible (960 Hz), a short echo time of 28 ms, and local shimming for the inferior frontal area. The matrix size was 64×64 and the field of view was 192×192 mm. Continuous coverage was obtained from +62 (A/P) to −46 (A/P).

Functional imaging data: analysis

The imaging data were analyzed using SPM5 (Statistical Parametric Mapping, Wellcome Trust Centre for Neuroimaging, London). Pre-processing of the data used SPM5 realignment, reslicing with sinc interpolation, normalisation to the MNI coordinate system (Montreal Neurological Institute) (Collins et al., 1994), and spatial smoothing with a 6 mm full width at half maximum isotropic Gaussian kernel. Unwarping was used in addition for the analysis of the data acquired for Investigation 2. Time series non-sphericity at each voxel was estimated and corrected for, and a high-pass filter with a cut-off period of 128 s was applied. For details on the fMRI analysis for Investigation 2 see Supplementary methods. For Investigation 2, in the single event design, a general linear model (GLM) was then applied to the time course of activation where the stimulus onsets ($t = 1$ s in each trial) were modelled as single impulse response functions and then convolved with the canonical hemodynamic response function (Friston et al., 1994). Linear contrasts were defined to test specific effects. Time derivatives were included in the basis functions set. Following smoothness estimation, in the first stage of analysis condition-specific experimental effects (parameter estimates, or regression coefficients, pertaining to the height of the canonical HRF) were obtained via the GLM in a voxel-wise manner for each subject. The results were obtained in a GLM model including the following regressors: regressors of temperature and flavor stimuli modelling the onset of the stimulus period, regressors of the button box responses made during the rating period, regressors of the neutral temperature and tasteless control stimuli, and regressors of the swallowing period. The GLM also included separate subject-specific regressors for the pleasantness and intensity ratings which were entered as parametric modulators for the regressors of the temperature and flavor stimuli. Subject-specific movement parameters were included as covariates of no interest. In the second (group random-effects) stage, subject-specific linear contrasts of these parameter estimates were entered into a series of one-sample *t*-tests, each constituting a group-level statistical parametric map. The correlation analyses of the fMRI BOLD (blood oxygenation-level dependent) signal with given parameters of interest (e.g. the pleasantness ratings) were performed at the second-level through applying one-sample *t*-tests to the first-level subject-specific parameter estimates resulting from performing linear parametric modulation as implemented in SPM5. We report results for brain regions where there were prior hypotheses on the basis of previous data. These regions have been previously shown to represent the reward value of taste, olfactory, flavor, somatosensory and temperature stimuli, and include the ventral prefrontal cortices, the pregenual cingulate cortex, and the ventral striatum (Craig et al., 2000; de Araujo et al., 2003a; de Araujo et al., 2003b; Kringelbach et al., 2003; McCabe and Rolls, 2007; Rolls and Grabenhorst, 2008; Rolls et al., 2003b). We applied small volume (false discovery rate) corrections for multiple comparisons for which $p < 0.05$ (though the exact corrected probability values are provided) (Genovese et al., 2002) with a radius corresponding to the full width at half maximum of the spatial smoothing filter used. In addition to the statistical criterion just described for a significant effect calculated for the peak voxel of a region of activation in an a priori defined region based on earlier findings, we used the additional statistical test (see Gottfried et al., 2002; O'Doherty et al., 2006; O'Doherty et al., 2003b) that the results reported were in global contrast and/or correlation analyses significant using the criterion of $p < 0.001$ uncorrected for multiple comparisons, and these additional statistics confirmed the same effects in the a priori regions in all cases. All results that were significant within the areas of interest for all the analyses performed are included in the Results section. In more detail, we used correlation analyses as implemented by parametric modulation in SPM to define regions where the BOLD signal correlated with the pleasantness ratings. These analyses were performed in an unbiased way separately for both investigations, and within each investigation, separately for both sensory modalities, hand temperature, and flavor. For locations where

significant correlations were found between the % BOLD signal change and the ratings, we produced graphs to show how the ratings were related to the % BOLD signal change. These were produced for each subject by taking the average of the BOLD response (in % BOLD signal change) in the 3 time bins at 4, 6 and 8 s post-stimulus, on each trial, and the corresponding rating. The voxels used for extracting BOLD signals were the peak voxels for the pleasantness correlation found in individual subjects. These were localized by drawing a 6 mm sphere around the group peak voxel and then localizing the individual subject's peak within that sphere. By restricting the selection of peak voxels for individual subjects to voxels located within 6 mm of the group peak we verified that all voxels for temperature and taste were in the same ventral prefrontal cortex region. For each subject the means were calculated in discretized ranges of the rating function (e.g. −2 to −1.75, −1.75 to −1.5 etc.), and then these values were averaged across subjects. The time course graphs in Fig. 4 were created by performing a finite impulse response (FIR) analysis as implemented in SPM5, in order to make no assumption about the time course based on the temporal filtering property of the haemodynamic response function.

Results

Investigation 1. Common representations of subjective pleasantness

In our first investigation, we aimed to identify brain regions that are involved in processing different kinds of rewards by combining in a new statistical analysis the results of two separate fMRI studies that independently investigated the neural correlates of subjective pleasantness for two different rewards. These were in two different sensory modalities, somatosensory (non-oral) temperature, and taste. Neural activations to a range of temperature and taste rewards were measured with fMRI (Grabenhorst et al., 2008a; Rolls et al., 2008a). Subjects provided ratings of the subjective pleasantness and intensity of the stimuli on each trial (see Supplementary results). The pleasantness and intensity ratings were used as subject-specific regressors for neural activations to find brain regions that track the subjective pleasantness or the subjective intensity of the temperature and taste rewards. This method of using subjective ratings as regressors for neural activations has previously been used to successfully identify brain areas where activity reflects the subjective affective value of stimuli when value is altered by presenting a range of affective stimuli or by feeding subjects to satiety (Grabenhorst and Rolls, 2008; Grabenhorst et al., 2007; Kringelbach et al., 2003).

To find brain regions that commonly track the subjective pleasantness of both temperature and taste rewards, we performed a statistical comparison where the statistical parametric maps of the individual subjects from both investigations were combined into a second-level, random-effects group analysis. This statistical analysis across temperature and taste stimuli revealed significant effects in the anterior ventral prefrontal cortex ([−28 52 −2] $z=3.38$, $p<0.006$ corrected; Fig. 1a), the pregenual cingulate cortex ([2 44 −2] $z=3.52$, $p<0.007$ corrected; Fig. 2a) and the ventral striatum ([−6 8 −16] $z=3.53$, $p<0.015$ corrected). To confirm that these effects were attributable to significant correlations for both temperature and taste stimuli and not due to a significant effect for only one type of stimulus, we also performed second-level, random-effects analyses separately for the temperature and the taste stimuli to identify areas of significant correlation within each stimulus modality. Significant effects in these analyses were found in the anterior ventral prefrontal

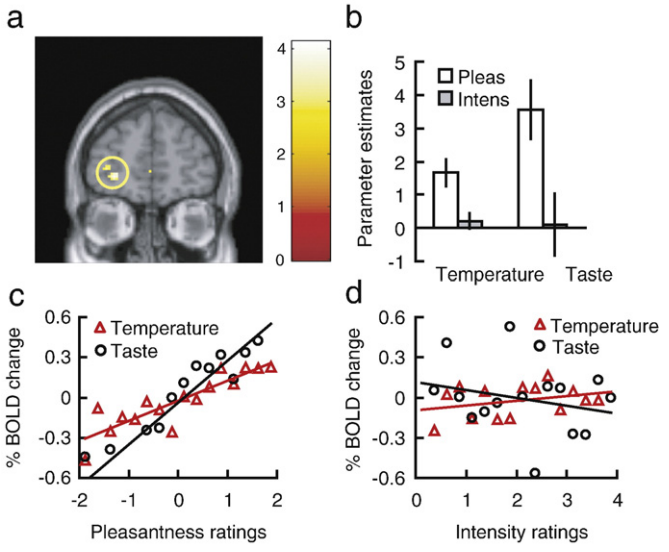

Fig. 1. Representation of subjective pleasantness in the ventral prefrontal cortex. (a) A region of the ventral prefrontal cortex where neural activity is correlated with subjective pleasantness ratings of both temperature and taste stimuli was identified in a combined group random-effects analysis based on two independent fMRI studies ($p<0.001$ corrected). (b) Parameter estimates (means ± s.e.m.) from a regression analysis where pleasantness and intensity ratings were used as regressors for neural activity. The parameter estimates can be interpreted as a measure of the effect size of the SPM correlation analysis. In the ventral prefrontal cortex there were significant effects of correlation between neural activity and the pleasantness ratings (Pleas) for both temperature and taste but no effects of correlation with the intensity ratings (Intens). (c) Correlations between the % BOLD signal change and the subjective pleasantness ratings for the temperature ($r=0.84$, $df=15$, $p=4\times10^{-4}$) and taste ($r=0.86$, $df=15$, $p=0.0002$) stimuli. (d) No correlation between the % BOLD signal change and the subjective intensity ratings for temperature ($r=0.32$, $df=14$, $p>0.27$) or taste ($r=-0.29$, $df=14$, $p>0.32$). The correlation graphs in this figure and the following figures were produced by taking the average of the BOLD response (in % BOLD signal change) in the 3 time bins at 4, 6 and 8 s post-stimulus, on each trial, and the corresponding rating. For each subject the means were calculated in discretized ranges of the rating function (e.g. −2 to −1.75, −1.75 to −1.5 etc.), and then these values were averaged across subjects.

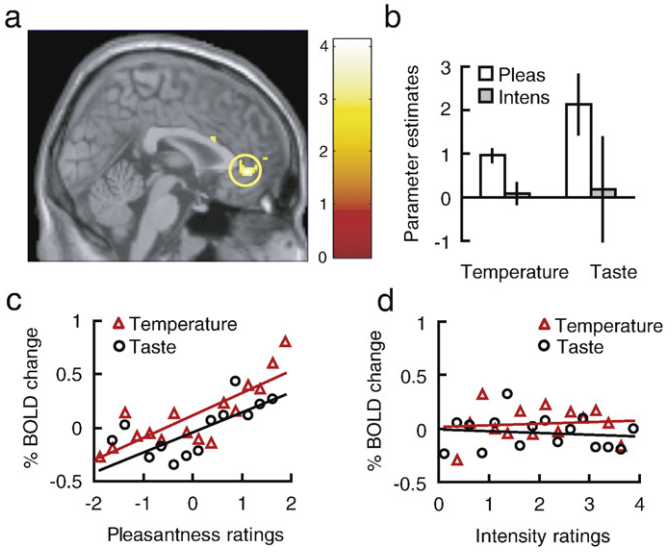

Fig. 2. Representation of subjective pleasantness in the pregenual cingulate cortex. (a) Neural activity in the pregenual cingulate cortex is correlated with subjective pleasantness ratings of both temperature and taste stimuli ($p<0.001$ corrected). (b) Parameter estimates (means ± s.e.m.) from a regression analysis where pleasantness and intensity ratings were used as regressors for neural activity. In the pregenual cingulate cortex there were significant effects of correlation between neural activity and the pleasantness ratings (Pleas) for both temperature and taste but no effects of correlation with the intensity ratings (Intens). (c) Correlations between the % BOLD signal change and the subjective pleasantness ratings for the temperature ($r=0.82$, $df=15$, $p=0.0001$) and taste ($r=0.76$, $df=15$, $p=0.002$) stimuli. (d) No correlation between the % BOLD signal change and the subjective intensity ratings for temperature ($r=0.10$, $df=14$, $p>0.73$) or taste ($r=-0.17$, $df=14$, $p=0.54$).

cortex for temperature ([−32 56 −6] $z=3.12$, $p<0.029$ corrected) and taste ([−28 52 −2] $z=3.09$, $p<0.016$ corrected), in the pregenual cingulate cortex for temperature ([4 38 −2] $z=4.24$, $p<0.001$ corrected) and taste ([4 44 −2] $z=3.24$, $p<0.016$), and in the ventral striatum for taste ([−6 10 −16] $z=3.64$, $p<0.006$ corrected) but not for temperature. A correlation with the pleasantness of temperature was found in a different, more anterior, part of the striatum at [−2 20 −4] ($z=3.25$ $p<0.041$ corrected). The overlap of the effects in ventral prefrontal cortex and pregenual cingulate cortex is shown in Supplementary Figure S2.

To further investigate the nature of the neural representation in these regions, we extracted the BOLD signal as a function of the subjective pleasantness ratings, as well as intensity ratings from the individual subjects. Neural activity in the ventral prefrontal cortex and pregenual cingulate cortex identified in the above analyses showed a clear linear increase related to the subjective pleasantness for both temperature and taste stimuli, and moreover the scale was similar, in that the slope of the relation between percentage BOLD change and subjective rating of pleasantness was similar for the temperature and taste stimuli (Figs. 1c and 2c). It is important to note, however, that the correlations were specific to pleasantness. There were no significant correlations between neural activity and subjective ratings of intensity in these regions for either temperature or taste (Figs. 1d and 2d). Consistently, no significant effects were found in these regions when the intensity ratings were used as regressors for neural activity in random-effects analyses. Further, another stimulus included in the protocol (Grabenhorst et al., 2008a), 0.4 M MSG, produced significantly ($p<0.05$) less activation in this prefrontal cortical area than 0.1 M MSG, and this indicates that intensity, which correlates with concentration (Bartoshuk and Cleveland, 1977), is not the basis of the activation in this ventral prefrontal region. It is consistent that the 0.1 M MSG was more pleasant than the 0.4 M MSG (Grabenhorst et al., 2008a).

Investigation 2. A common neural scale for subjective pleasantness

These findings provide support for the idea that there are common brain regions that linearly track the subjective pleasantness of different kinds of rewards. However, the analysis combined data from studies conducted on different groups of subjects. It cannot, therefore, show whether there are voxels in the same subjects that show activations that relate to pleasantness in the two modalities. We therefore carried out a new experiment on a new group of subjects.

In this experiment, the rewards were pleasant and unpleasant somatosensory (non-oral) temperature stimuli and pleasant and unpleasant flavored liquid food stimuli (see Materials and methods). On each trial subjects were presented with either a temperature or a flavor stimulus and asked to rate the subjective pleasantness of the stimulus. Subjects also provided ratings of the non-affective, sensory properties of the stimuli including ratings of the intensity of the temperature stimuli and the fattiness of the flavor stimuli. The mean coefficient of variation across all subjects and stimuli, a measure of the relative variability of the pleasantness ratings within subjects, was 0.26 ± 0.01 (mean ± s.e.m.).

The affective and non-affective subjective ratings were used as subject-specific regressors in the fMRI analyses to find brain regions where activations during the time of the stimulus presentation correlated with the subjective ratings for the temperature or flavor stimuli. The resulting statistical parametric maps of the individual subjects were then entered into second-level, random-effects group analyses performed separately for the temperature and flavor stimuli. Significant correlations in the stimulus-specific analysis were found in the ventral prefrontal cortex (see Supplementary Table 1 for a complete list of results). The peak coordinates for correlated activity in the ventral prefrontal cortex in the individual analyses were [−26 48 2] ($z=3.67$, $p<0.009$ corrected) for temperature, and [−30 46 4]

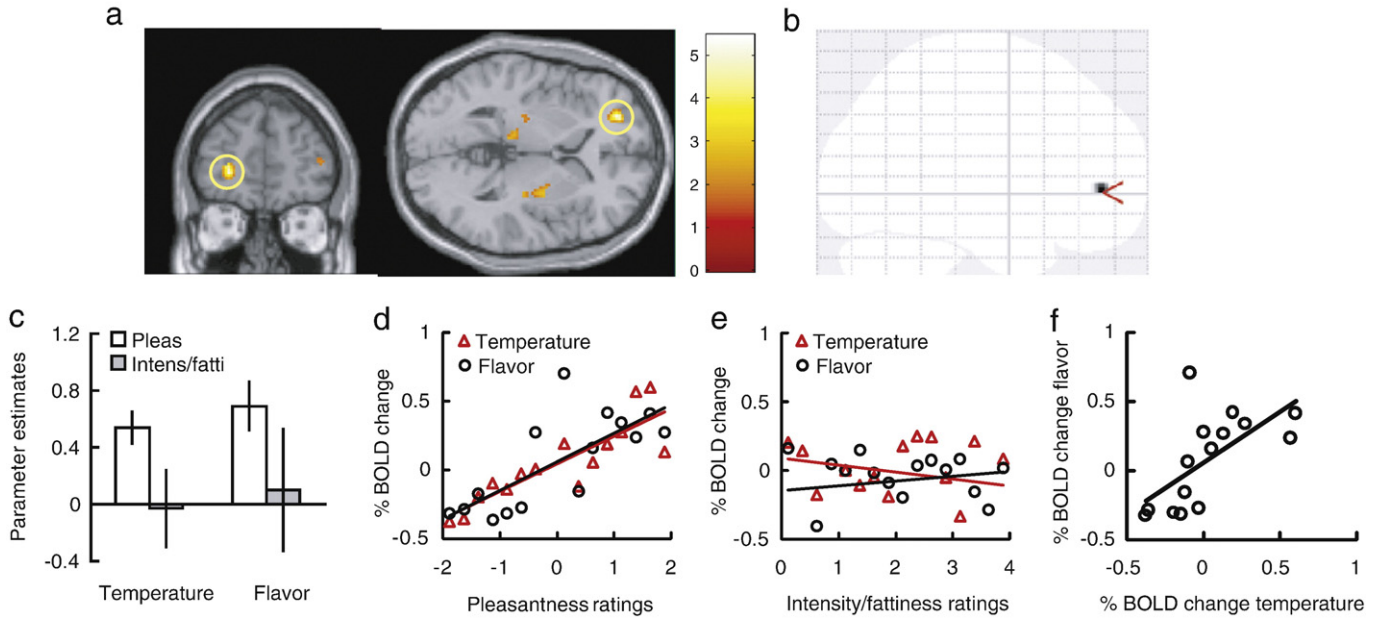

Fig. 3. A common scale for subjective pleasantness in the ventral prefrontal cortex. (a) The ventral prefrontal cortex showed a common effect of correlation with the subjective pleasantness ratings for both temperature and flavor stimuli as identified by an inclusive masking analysis based on a within-subjects comparison. (Thresholded to show the extent of the common effect.) (b) The ventral prefrontal cortex was the only region to show this effect as revealed by an inclusive masking analysis thresholded at 0.005. (c) Parameter estimates (means ± s.e.m.) from a regression analysis where pleasantness and intensity ratings were used as regressors for neural activity. In the ventral prefrontal cortex there were significant effects of correlation between neural activity and the pleasantness ratings (Pleas) for both temperature and flavor but no effects of correlation with the intensity or fattiness ratings (Intens/fatti). (d) Correlations between the % BOLD signal change and the subjective pleasantness ratings for the temperature ($r=0.86$, $p=4\times10^{-4}$) and flavor ($r=0.74$, $p=0.001$) stimuli in the ventral prefrontal cortex. The slope and intercept of the regression lines were not different for the temperature and flavor stimuli. (e) There was no correlation between the % BOLD signal change and the subjective intensity ($r=-0.24$, $p>0.38$) or fattiness ($r=0.18$, $p>0.49$) ratings. (f) Correlation between the % BOLD signal for the temperature stimuli and the % BOLD signal for the flavor stimuli ($r=0.63$, $p=0.01$). The % BOLD signal was extracted for both types of stimuli for given ranges of values on the pleasantness rating scale.

($z = 3.43$, $p < 0.016$ corrected), [−28 52 2] ($z = 3.24$, $p < 0.023$ corrected) for flavor. To reveal brain regions that commonly track the subjective pleasantness of both temperature and flavor stimuli, we inclusively masked ($p < 0.005$) the statistical parametric maps resulting from the stimulus-specific random-effects analyses. The ventral prefrontal cortex was the only region to show a correlation with the subjective pleasantness ratings of both temperature and flavor stimuli (Figs. 3a, b). We used the probabilistic cytoarchitectonic atlas as implemented in the SPM Anatomy toolbox (Eickhoff et al., 2005) to confirm that the effect was in the orbital gyrus and was located outside the boundaries of Brodmann areas 44 and 45. By using the statistical map generated in Investigation 1 as an inclusive mask we were able to verify that this area corresponds to the ventral prefrontal cortex site identified by the between-studies comparison in Investigation 1. (The extent of the effects found for temperature and flavor in the ventral prefrontal cortex is shown in Supplementary Fig. S3.) This result replicates the finding of the between-studies comparison that the ventral prefrontal cortex provides a neural representation of temperature and flavor rewards. However, we did not find a common activation for the pregenual cingulate cortex or the ventral striatum as identified in Investigation 1. A significant effect in the pregenual cingulate cortex was found only for the flavor stimuli at [12 50 −8] ($z = 2.98$, $p < 0.05$ corrected).

If there are voxels that are activated in common in relation to the two rewards, the slope and intercept of the regression line should be the same for the different types of reward. To test whether the ventral prefrontal cortex provides a representation of subjective pleasantness for temperature and flavor rewards on the same neural scale in this sense, we extracted the BOLD signal from the identical voxels within each individual subject for both types of stimuli which were the peak voxels to show a correlation in the inclusive masking analysis. We then plotted the BOLD signal averaged across subjects as a function of the pleasantness rating scale. If the slope and intercept of this linear relationship are similar for different types of reward this is an indication that the rewards are represented on the same scale of neural activity. Fig. 3d shows that for the ventral prefrontal cortex, the regression lines are highly similar for the temperature and flavor stimuli. A formal statistical test revealed that the slopes of both regression lines are not significantly different from each other. The slope ± standard error for temperature = 0.20 ± 0.03; the slope for flavor = 0.21 ± 0.05; and these do not differ ($F(1, 27) = 0.01$; $p > 0.92$). The intercept for temperature = 0.0043, and for flavor = 0.0059, and these do not differ ($F(1, 27) = 0.03$; $p > 0.8$). To directly compare the BOLD signal for the temperature and flavor stimuli for corresponding levels of pleasantness we plotted the BOLD signal from the ventral prefrontal cortex for temperature against the BOLD signal for flavor (Fig. 3f). The correlation plot in Fig. 3f was constructed by extracting the BOLD signal values for both types of stimuli that were associated with values of a given bin on the pleasantness rating scale. The analysis revealed a significant correlation between the BOLD signal for temperature and flavor with $r = 0.63$, $p = 0.01$. We also tested whether the difference in BOLD signal in the ventral prefrontal cortex between the flavor and temperature trials was different from zero across the pleasantness rating scale. A one-sample t-test showed that the mean difference is not significantly different from zero ($t = 0.77$; $df = 14$; $p > 0.45$; with the lower and upper boundaries for a 95% confidence interval being −0.2 and 0.1, respectively). Further, in within-subjects analyses of the correlation between the activations to the pleasantness of the temperature and flavor stimuli, it was found that there was a positive correlation between the BOLD signal of temperature and flavor, with the mean correlation across subjects $r = 0.51 \pm 0.1$ (s.e.m.), $p < 0.001$.

We further extracted the time courses of the BOLD signal from the ventral prefrontal cortex for both temperature and flavor stimuli as a function of pleasantness ratings (Fig. 4). Inspection of the time courses confirms that neural responses in this brain area are clearly related to the subjective pleasantness of the stimuli. They also suggest that the correlation arose from neural activity that was evoked by the presentation of the stimuli. To check this we performed a control analysis. In this, the pleasantness ratings were used as regressors for neural activity that was measured during the time when the subjects made responses so as to rate the pleasantness. There was no correlation in the ventral prefrontal cortex even at a low statistical threshold ($p < 0.01$).

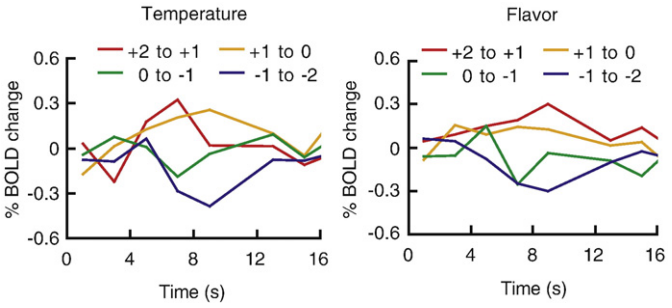

Fig. 4. Average time courses of the % BOLD signal change from the ventral prefrontal cortex for temperature (left) and flavor (right). Time courses are color-coded according to pleasantness ratings. The time courses in the ventral prefrontal cortex are clearly graded as a function of subjective pleasantness for both types of rewards. This effect occurs time-locked with respect to the onset of the stimuli ($t = 0$ s).

As in the first investigation, we further checked whether the results for pleasantness were confounded by differences in the non-affective properties of the rewards. To do this we used the subjective ratings of intensity and fattiness as regressors for the neural activity. We did not find any significant effects in the ventral prefrontal cortex in these control statistical tests, and this confirms the findings from Investigation 1 (Figs. 3 c, e). In Investigation 2 we did not obtain intensity ratings for the flavor stimuli and so could not include intensity as an additional regressor for the flavor trials. Therefore, variations in intensity that are independent of fat content might potentially have contributed to some of the effects observed. However, in a previous study where intensity ratings of flavor stimuli were correlated with neural activity, no effects were found in the ventral prefrontal cortex (de Araujo et al., 2003b).

The fact that similar effects were found in Investigations 1 and 2 with different participants strengthens the conclusions reached, in that each study validates the other with independent data. Moreover, we performed a cross-validation procedure for our main analysis in Investigation 2 where we used one half of the subject sample to identify a region of interest in a second-level SPM correlation analysis and then used the other half of the subject sample to extract the data from this region for subsequent analysis. The results of the cross-validation procedure were highly similar to the results described above and are shown in the Supplementary material and Supplementary Figure S4.

In both investigations we looked for activations that increased with subjective pleasantness. However, there may also be activations that increase with salience (O'Doherty, 2004). These should show a high activation in response to both affectively positive and negative stimuli compared with affectively neutral stimuli. We therefore performed a contrast analysis between activations produced by the temperature and flavor stimuli and the neutral or tasteless control stimuli which were delivered later on each trial (see Materials and methods). Two separate analyses were performed. In one we contrasted activations produced by the pleasant warm and unpleasant cold temperature stimuli with activations produced by the neutral temperature control stimulus. In the other we contrasted activations produced by the pleasant vanilla-flavored and unpleasant strawberry-flavored stimuli with activations produced by the tasteless rinse

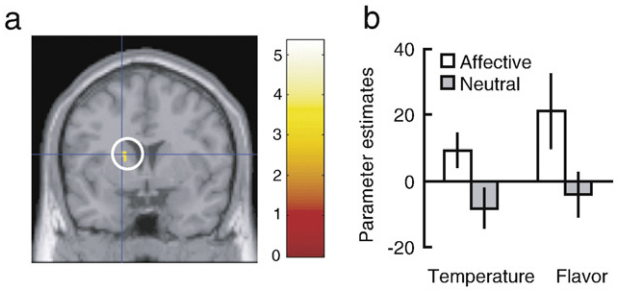

Fig. 5. Salience coding in the striatum. (a) The caudate nucleus was more strongly activated by salient stimuli than by neutral stimuli for both temperature and flavor stimuli as shown by an inclusive masking analysis ($p<0.005$) between contrasts of salient (pleasant and unpleasant) temperature vs. neutral temperature and salient (pleasant and unpleasant) flavor vs. tasteless control solution. (b) Parameter estimates (means ± s.e.m.) showing differential effects in the striatum between affective, salient stimuli (Affective) and neutral stimuli (Neutral) for both temperature and flavor.

stimulus. (See Supplementary Table 2 for a complete list of results of the individual contrasts.) Next, so as to reveal brain regions that responded to both salient temperature and flavor stimuli compared with neutral stimuli, we inclusively masked ($p<0.005$) the statistical parametric maps resulting from these two contrasts.

This analysis revealed an overlap of significant effects in the ventral striatum at [16 16 −6] ($z=3.25$, $p<0.001$ corrected) and caudate nucleus at [−18 4 14] ($z=3.33$, $p<0.001$ corrected) (Fig. 5). Another peak of common activation was found in the dorsolateral prefrontal cortex at [50 28 30] ($z=3.82$, $p<0.001$ corrected). No correlations with pleasantness were found in these locations. This means either that there was not enough statistical power in the present study, or that common regions in the striatum represent motivationally salient stimuli but may not represent subjective pleasantness for different rewards on a linear scale.

Discussion

The results indicate that the ventral prefrontal cortex represents the subjective pleasantness of two fundamentally different reinforcers, somatosensory temperature and flavor, on a common scale of neural activity. We obtained consistent evidence from a between-group comparison which involved a combined analysis of two independent fMRI experiments (Fig. 1) and from a within-group study in the same subjects (Fig. 3). In the second study, the slope and intercept for the regression lines describing the relationship between neural activations and subjective pleasantness ratings were highly similar for the rewards in the different modalities (Fig. 3d), and here the data were read from the same voxels. The peak of activation in the ventral prefrontal cortex lay in area 47/12, which includes the inferior convexity cortex and lateral orbitofrontal cortex (Petrides and Pandya, 2002).

The common activation in the ventral prefrontal cortex cannot simply be explained as a multisensory response. It is true that there are single neurons in the orbitofrontal cortex that fire for the taste, smell and sight of food (Rolls and Baylis, 1994) and represent reward value in all three sensory modalities (Critchley and Rolls, 1996), and that there are activations in common in the human orbitofrontal cortex for taste and smell (de Araujo et al., 2003b). Also, anatomical tracing studies show that the ventral prefrontal convexity receives inputs both from the primary taste cortex (Yaxley et al., 1990) in the anterior insula and the secondary somatosensory cortex SII (Carmichael and Price, 1995) which responds to temperature (Craig et al., 2000). Furthermore, the same injection of a fluorescent tracer into the ventrolateral area 47/12 labels both anterior insula and SII as shown for case 5 in Petrides and Pandya (2002). The same case also shows that this area is closely interconnected with the more medial orbitofrontal cortex.

However, the common activation in Investigation 2 was found when relating activity to ratings of subjective pleasantness. The connectivity of the ventral prefrontal and orbitofrontal cortex is ideally suited for integrating information about the identity of sensory stimuli and the reward value related to these stimuli (Barbas, 1988). Critchley and Rolls (1996) and Rolls et al. (1989) have shown that neurons in the orbitofrontal cortex represent the reward value of sensory stimuli in that they reduce their firing to a particular food when it is eaten to satiety, but not to other types of foods, and the change in firing to each type of food reflects the change in the reward value of both types of food (Critchley and Rolls, 1996; Rolls, 2007). The same results have been found in fMRI studies using the same manipulation (Gottfried et al., 2003; Kringelbach et al., 2003). These studies indicate that activity in the ventral and orbitofrontal cortices is involved in representing stimuli in terms of their reward value. Padoa-Schioppa and Assad (2006, 2008) have also reported that neurons in the orbitofrontal cortex show similar activity for two different rewards. As pointed out in the Introduction, the rewards used in that study were similar, that is different types of juice. It is for this reason that in the present study we deliberately chose an oral (flavor) and a tactile (somatosensory temperature) reward, and related the activations to the subjective ratings for each reward.

In previous work, activations to different types of reward have been found that are somewhat consistent with those reported here, though not obtained in the same experimental runs in the same subjects as in Investigation 2. For example, the pleasantness of touch to the forearm which may be related to activity in CT afferent fibres (Olausson et al., 2010) activates a (contralateral) region of the ventral prefrontal cortex ([26 50 −8] extending up to [26 50 0] (McCabe et al., 2008), close to that described here. Further, a word label indicating that a touch will be rich moisturizing cream activated a ventral prefrontal region [−22 50 10] very close to that described here (McCabe et al., 2008). In addition, monetary reward activates a nearby region ([−30 38 −2] as illustrated in Fig. 3 of Rolls et al. (2008b)). An earlier study (Royet et al., 2000) compared changes in regional cerebral blood flow produced by emotional (pleasant and unpleasant) and neutral olfactory, visual, and auditory stimuli. The results indicated that increases in blood flow in a region of the orbitofrontal cortex can be produced by emotional (pleasant and unpleasant) compared to neutral stimuli in all three sensory modalities. However, the study did not investigate common scaling of pleasantness. The present study though extends these earlier findings by showing that flavor as well as thermal reward activate the same region within subjects, and that the activations are on the same scale.

In the present study, activations related to the pleasantness of both flavor and temperature rewards were found in a lateral orbital region of the prefrontal cortex. Support for some roles of the anterolateral orbitofrontal cortex in reward processing is that in an investigation with hedonically complex odor stimuli that included positive and negative components, activations were correlated with subjective pleasantness in the anterolateral orbitofrontal cortex [40 52 −6] (Grabenhorst et al., 2007). Further, encoding of the relative pleasantness of olfactory stimuli was found in the anterolateral orbitofrontal cortex [−38 48 −12] by Grabenhorst and Rolls (2009); activations to pleasant odors (but not to unpleasant odors) have been reported in the anterolateral orbitofrontal cortex [−42 42 −12] (Royet et al., 2003); and in a monetary reward/loss task, activations in the anterolateral orbitofrontal cortex were related to reward minus loss [−39 42 −15] (O'Doherty et al., 2003a). In a previous study, activations were correlated with the unpleasantness of 6 odors in different parts of the lateral orbitofrontal cortex (at [−20 54 −14] and [−16 28 −18]) (Rolls et al., 2003a).

Importantly, the relationship between neural activity and subjective ratings of different affective stimuli in the ventral prefrontal cortex was specific for the subjective pleasantness of the stimuli and was not evident for their sensory, non-affective properties (Fig. 3e). In our design pleasantness and intensity ratings were not correlated (Supplementary Figure S1). We note that, in general, taste

pleasantness and intensity may be somewhat related in that, for example, as the concentration of a glucose taste increases, within limits there will be some change of both pleasantness and intensity. However, it has been demonstrated that pleasantness and intensity are in principle dissociable as shown for example by sensory-specific satiety where the subjective pleasantness of a food decreases while its subjective intensity remains unchanged (Rolls et al., 1983). Further, dissociations between the neural representation of pleasantness and intensity have been demonstrated in previous fMRI studies for different sensory modalities (Grabenhorst and Rolls, 2008; Grabenhorst and Rolls, 2009; Grabenhorst et al., 2007; Rolls et al., 2008a).

Further, the relationship between neural activity and subjective ratings of different affective stimuli in the ventral prefrontal cortex could not be explained by salience or motivation, because no activations related to salience were found in the ventral prefrontal or orbitofrontal cortex. This is consistent with evidence that the activity of cells in the orbitofrontal cortex is related to the reward value of stimuli, whereas activity in other areas reflects the degree of motivation associated with the stimuli, as manipulated both by rewards (positive) and punishment (negative) (Roesch and Olson, 2004). We note for completeness that brain regions where neural activity correlated with the subjective intensity of the thermal stimuli in Investigation 1 included the somatosensory cortex and the mid-posterior and anterior insular cortex (Rolls et al., 2008a). Consistently, in other studies activations produced by thermal stimuli in these brain regions were correlated with ratings of intensity (Craig et al., 2000) and pain (Baliki et al., 2009), although in these studies no separate ratings of the affective vs. non-affective properties of thermal stimuli were taken.

The pregenual cingulate cortex was identified in Investigation 1 as a region where the pleasantness of both temperature and taste is represented, but no common activation for this region was found in the within-group comparison in Investigation 2. A correlation with subjective pleasantness was found in this region only for the flavor stimuli. There could be two reasons. First, Investigation 1 had higher statistical power because there were more trials for each stimulus. Second, Investigation 1 used a larger set of temperature stimuli which resulted in a broader range of pleasantness ratings. The pregenual cingulate cortex has connections with the ventral prefrontal area 47/12 (Petrides and Pandya, 2002), and activations in this region have been shown to track the subjective value of different rewards such as flavor (Grabenhorst et al., 2010), chocolate (Rolls and McCabe, 2007) and money (Kable and Glimcher, 2007). However, these studies did not look for peaks of activation in common for different rewards. Both area 47/12 and the pregenual cingulate cortex have connections with medial area 10 of the prefrontal cortex (Carmichael and Price, 1996). This area is involved not only in representing affective value but additionally in choice decision-making on the basis of value (Daw et al., 2006; Grabenhorst et al., 2008b; Rolls and Grabenhorst, 2008; Rolls et al., 2010). We suggest that information about the subjective pleasantness of different types of reward from area 47/12 and the pregenual cingulate cortex acts as an input into a decision-making process in medial prefrontal cortex area 10 when choices between qualitatively different rewards are required.

In Investigation 2 we found activations in common for temperature and flavor in the ventral striatum, but only when we compared both pleasant and unpleasant stimuli with neutral stimuli. It was this comparison with neutral stimuli that had been used in a previous study looking for common activations for monetary and social stimuli (Izuma et al., 2008). However, in Investigation 2 the common neural activations in the ventral striatum did not scale linearly with the subjective pleasantness of both rewards. This is consistent with studies showing that some regions of the striatum encode the salience of monetary rewards (Zink et al., 2004) and respond to both pleasant and unpleasant salient stimuli (Jensen et al., 2007; Seymour et al., 2004).

We conceptualize subjective pleasantness as the subjective correlate of reward value, that is, the subjectively reported affective value of a goal for action (Rolls and Grabenhorst, 2008). We note that motivation, the wanting for a stimulus (Berridge et al., 2009), can be understood as the state in which work will be performed to obtain a goal (Rolls, 2005). (The striatum may be especially linked to wanting (Berridge et al., 2009), in that it is involved in wanting produced by well learned conditioned stimuli when behavior is no longer under the control of the rewarding goal object, but is being performed more as a habit (Rolls, 2005).) The concept of subjective or experienced pleasantness as used in the present report is thus closely related to the concept of "experienced utility" (Kahneman et al., 1997), that is, a hedonic interpretation of utility which can be measured by reports of subjective experience. This is different from the concept of "decision utility" (Kahneman et al., 1997) which is an operational measure of value inferred from choices and is often referred to as "subjective value" (Kable and Glimcher, 2007). It will be important in future studies to investigate how the common representation of subjective pleasantness as identified in the present study is involved when subjects make economic choices about different rewards. Another strategy is to vary parametrically the expected value of an outcome, for example of a monetary reward, before a decision is made, and identify brain regions where neural activity correlates with changes in expected value as well as other parameters, including risk (Knutson and Bossaerts, 2007; Preuschoff et al., 2006). Neural correlates of expected value have been found for monetary rewards in the orbitofrontal cortex (Rolls et al., 2008b) and ventral striatum (Preuschoff et al., 2006), and for taste rewards in the orbitofrontal cortex and ventral striatum (O'Doherty et al., 2002), but to our knowledge no investigation has directly compared expected value for qualitatively different types of rewards. The present study does show effects for the pleasantness of different primary reinforcers, and this is the subjective correlate of reward magnitude (Rolls et al., 2008b).

It is important to note that our finding that activity in the same prefrontal cortex voxels correlates with the subjective pleasantness of different rewards does not prove that there is a common representation of reward value at the level of single neurons. A typical fMRI voxel contains as many as 5.5 million neurons (Logothetis, 2008). It is therefore not possible to use fMRI to distinguish whether there are single neurons in the ventral prefrontal cortex that encode the subjective reward value of different rewards, or whether there are different populations of neurons within the same voxels that separately encode the value of different rewards. However, part of the significance of our finding is that we have demonstrated the existence of a specific region in the human brain where neural activity reflects the subjective pleasantness of qualitatively different primary rewards.

From a computational perspective, if the reward value of different stimuli is encoded by different populations of neurons, it would be advantageous if these neurons were located closely together in the neocortex, as this would allow for competitive interactions to occur between these neuronal populations. The reason is that connections, including those of the inhibitory interneurons, are relatively short-range, within a few mm, in the neocortex (Rolls, 2008). The competitive interactions and learning could result in neurons learning to respond to particular combinations of sensory stimuli that together produce potent reward (as in combinations of taste and odor (McCabe and Rolls, 2007), and in scaling of different rewards relative to each other (Rolls, 2005, 2008)).

With our current understanding of how decisions are made using attractor networks, it is important that different rewards compete on the same scale to win in the attractor competition (Deco and Rolls, 2006; Deco et al., 2009). Part of the significance of our findings is that they suggest that the representations in these regions are on a similar scale. However, it must be noted that the exact scaling into the decision-making attractor network will be set by the number of inputs from each source, by their firing rates, and by the strengths of the synapses that introduce the different inputs into the decision-making

network (Deco and Rolls, 2006; Deco et al., 2009; Rolls, 2008). When the decision is taken, it is between different goals with different values, and the values must be on the same scale. The winner is the representation of one of the goals. In this sense, the concept investigated here is that different rewards need to be expressed on a similar scale for decision-making to operate correctly. However, this need not imply conversion into a new representation that is of a common currency of general reward (Rolls and Grabenhorst, 2008). In the decision process itself it is important to know which reward has won, and the mechanism is likely to involve competition between different rewards represented close together in the cerebral cortex, rather than convergence of different rewards onto the same neuron (Deco and Rolls, 2006; Deco et al., 2009; Rolls, 2008). The evidence that different rewards are encoded by different neurons in the orbitofrontal cortex and related areas comes from single neuron recording studies in macaques, which show that different neurons respond to the different sensory properties that define different rewards, and that the neurons in these regions represent sensory-specific satiety, the change in the pleasantness of one reward but not of other rewards after a particular reward has been consumed (Rolls, 2005; Rolls and Grabenhorst, 2008). The concept that the decision-making mechanism involves competition between different attractor networks, each representing a different reward but competing through the short-range inhibitory neurons in the cortex, is developed by Rolls and Deco (2010).

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Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2010.03.043.

References

Baliki, M.N., Geha, P.Y., Apkarian, A.V., 2009. Parsing pain perception between nociceptive representation and magnitude estimation. J. Neurophysiol. 101, 875–887.
Barbas, H., 1988. Anatomic organization of basoventral and mediodorsal visual recipient prefrontal regions in the rhesus monkey. J. Comp. Neurol. 276, 313–342.
Bartoshuk, L.M., Cleveland, C.T., 1977. Mixtures of substances with similar tastes. A test of a psychophysical model of taste mixture interactions. Sens Processes 1, 177–186.
Bernoulli, J., 1738 / 1954. Exposition of a new theory on the measurement of risk. Econometrica 22, 23–36.
Berridge, K.C., Robinson, T.E., Aldridge, J.W., 2009. Dissecting components of reward: 'liking', 'wanting', and learning. Curr. Opin. Pharmacol. 9, 65–73.
Cabanac, M., 1992. Pleasure: the common currency. J. Theor. Biol. 155, 173–200.
Carmichael, S.T., Price, J.L., 1995. Sensory and premotor connections of the orbital and medial prefrontal cortex of macaque monkeys. J. Comp. Neurol. 363, 642–664.
Carmichael, S.T., Price, J.L., 1996. Connectional networks within the orbital and medial prefrontal cortex of macaque monkeys. J. Comp. Neurol. 371, 179–207.
Collins, D.L., Neelin, P., Peters, T.M., Evans, A.C., 1994. Automatic 3D intersubject registration of MR volumetric data in standardized Talairach space. J. Comput. Assist. Tomogr. 18, 192–205.
Craig, A.D., Chen, K., Bandy, D., Reiman, E.M., 2000. Thermosensory activation of insular cortex. Nat. Neurosci. 3, 184–190.
Critchley, H.D., Rolls, E.T., 1996. Hunger and satiety modify the responses of olfactory and visual neurons in the primate orbitofrontal cortex. J. Neurophysiol. 75, 1673–1686.
Daw, N.D., O'Doherty, J.P., Dayan, P., Seymour, B., Dolan, R.J., 2006. Cortical substrates for exploratory decisions in humans. Nature 441, 876–879.
de Araujo, I.E.T., Kringelbach, M.L., Rolls, E.T., Hobden, P., 2003a. The representation of umami taste in the human brain. J. Neurophysiol. 90, 313–319.
de Araujo, I.E.T., Rolls, E.T., Kringelbach, M.L., McGlone, F., Phillips, N., 2003b. Taste-olfactory convergence, and the representation of the pleasantness of flavour, in the human brain. Eur. J. Neurosci. 18, 2059–2068.
de Araujo, I.E.T., Rolls, E.T., Velazco, M.I., Margot, C., Cayeux, I., 2005. Cognitive modulation of olfactory processing. Neuron 46, 671–679.
Deco, G., Rolls, E.T., 2006. Decision-making and Weber's Law: a neurophysiological model. Eur. J. Neurosci. 24, 901–916.
Deco, G., Rolls, E.T., Romo, R., 2009. Stochastic dynamics as a principle of brain function. Prog. Neurobiol. 88, 1–16.
Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., Zilles, K., 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. Neuroimage 25, 1325–1335.
Friston, K.J., Worsley, K.J., Frackowiak, R.S.J., Mazziotta, J.C., Evans, A.C., 1994. Assessing the significance of focal activations using their spatial extent. Hum. Brain Mapp. 1, 214–220.
Genovese, C.R., Lazar, N.A., Nichols, T., 2002. Thresholding of statistical maps in functional neuroimaging using the false discovery rate. Neuroimage 15, 870–878.
Gottfried, J.A., O'Doherty, J., Dolan, R.J., 2002. Appetitive and aversive olfactory learning in humans studied using event-related functional magnetic resonance imaging. J. Neurosci. 22, 10829–10837.
Gottfried, J.A., O'Doherty, J., Dolan, R.J., 2003. Encoding predictive reward value in human amygdala and orbitofrontal cortex. Science 301, 1104–1107.
Grabenhorst, F., Rolls, E.T., 2008. Selective attention to affective value alters how the brain processes taste stimuli. Eur. J. Neurosci. 27, 723–729.
Grabenhorst, F., Rolls, E.T., 2009. Different representations of relative and absolute value in the human brain. Neuroimage 48, 258–268.
Grabenhorst, F., Rolls, E.T., Bilderbeck, A., 2008a. How cognition modulates affective responses to taste and flavor: top down influences on the orbitofrontal and pregenual cingulate cortices. Cereb. Cortex 18, 1549–1559.
Grabenhorst, F., Rolls, E.T., Margot, C., da Silva, M.A.A.P., Velazco, M.I., 2007. How pleasant and unpleasant stimuli combine in different brain regions: odor mixtures. J. Neurosci. 27, 13532–13540.
Grabenhorst, F., Rolls, E.T., Parris, B.A., 2008b. From affective value to decision-making in the prefrontal cortex. Eur. J. Neurosci. 28, 1930–1939.
Grabenhorst, F., Rolls, E.T., Parris, B.A., D'Souza, A., 2010. How the brain represents the reward value of fat in the mouth. Cerebral Cortex, Electronic publication 14 August 2009 20 (5), 1082–1091.
Izuma, K., Saito, D.N., Sadato, N., 2008. Processing of social and monetary rewards in the human striatum. Neuron 58, 284–294.
Jensen, J., Smith, A.J., Willeit, M., Crawley, A.P., Mikulis, D.J., Vitcu, I., Kapur, S., 2007. Separate brain regions code for salience vs. valence during reward prediction in humans. Hum. Brain Mapp. 28, 294–302.
Kable, J.W., Glimcher, P.W., 2007. The neural correlates of subjective value during intertemporal choice. Nat. Neurosci. 10, 1625–1633.
Kahneman, D., Wakker, P.P., Sarin, R., 1997. Back to Bentham? Explorations of experienced utility. Q. J. Econ. 112, 375–405.
Knutson, B., Bossaerts, P., 2007. Neural antecedents of financial decisions. J. Neurosci. 27, 8174–8177.
Kringelbach, M.L., O'Doherty, J., Rolls, E.T., Andrews, C., 2003. Activation of the human orbitofrontal cortex to a liquid food stimulus is correlated with its subjective pleasantness. Cereb. Cortex 13, 1064–1071.
Logothetis, N.K., 2008. What we can do and what we cannot do with fMRI. Nature 453, 869–878.
McCabe, C., Rolls, E.T., 2007. Umami: a delicious flavor formed by convergence of taste and olfactory pathways in the human brain. Eur. J. Neurosci. 25, 1855–1864.
McCabe, C., Rolls, E.T., Bilderbeck, A., McGlone, F., 2008. Cognitive influences on the affective representation of touch and the sight of touch in the human brain. Soc. Cogn. Affect. Neurosci. 3, 97–108.
McFarland, D.J., Sibly, R.M., 1975. The behavioural final common path. Philos. Trans. R. Soc. Lond. B Biol. Sci. 270, 265–293.
Montague, P.R., Berns, G.S., 2002. Neural economics and the biological substrates of valuation. Neuron 36, 265–284.
O'Doherty, J., Critchley, H., Deichmann, R., Dolan, R.J., 2003a. Dissociating valence of outcome from behavioral control in human orbital and ventral prefrontal cortices. J. Neurosci. 23, 7931–7939.
O'Doherty, J.P., 2004. Reward representations and reward-related learning in the human brain: insights from neuroimaging. Curr. Opin. Neurobiol. 14, 769–776.
O'Doherty, J.P., Buchanan, T.W., Seymour, B., Dolan, R.J., 2006. Predictive neural coding of reward preference involves dissociable responses in human ventral midbrain and ventral striatum. Neuron 49, 157–166.
O'Doherty, J.P., Dayan, P., Friston, K., Critchley, H., Dolan, R.J., 2003b. Temporal difference models and reward-related learning in the human brain. Neuron 38, 329–337.
O'Doherty, J.P., Deichmann, R., Critchley, H.D., Dolan, R.J., 2002. Neural responses during anticipation of a primary taste reward. Neuron 33, 815–826.
Olausson, H., Wessberg, J., Morrison, I., McGlone, F., Vallbo, A., 2010. The neurophysiology of unmyelinated tactile afferents. Neurosci. Biobehav. Rev. 34, 185–191.
Padoa-Schioppa, C., Assad, J.A., 2006. Neurons in the orbitofrontal cortex encode economic value. Nature 441, 223–226.
Padoa-Schioppa, C., Assad, J.A., 2008. The representation of economic value in the orbitofrontal cortex is invariant for changes of menu. Nat. Neurosci. 11, 95–102.
Petrides, M., Pandya, D.N., 2002. Comparative cytoarchitectonic analysis of the human and the macaque ventrolateral prefrontal cortex and corticocortical connection patterns in the monkey. Eur. J. Neurosci. 16, 291–310.
Preuschoff, K., Bossaerts, P., Quartz, S.R., 2006. Neural differentiation of expected reward and risk in human subcortical structures. Neuron 51, 381–390.
Roesch, M.R., Olson, C.R., 2004. Neuronal activity related to reward value and motivation in primate frontal cortex. Science 304, 307–310.
Rolls, E.T., 1999. The Brain and Emotion. Oxford University Press, Oxford.
Rolls, E.T., 2005. Emotion Explained. Oxford University Press, Oxford.
Rolls, E.T., 2007. Sensory processing in the brain related to the control of food intake. Proc. Nutr. Soc. 66, 96–112.

Rolls, E.T., 2008. Memory, Attention, and Decision-Making: A Unifying Computational Neuroscience Approach. Oxford University Press, Oxford.
Rolls, E.T., Baylis, L.L., 1994. Gustatory, olfactory, and visual convergence within the primate orbitofrontal cortex. J. Neurosci. 14, 5437–5452.
Rolls, E.T., Deco, G., 2010. The Noisy Brain: Stochastic Dynamics as a Principle of Brain Function. Oxford University Press, Oxford.
Rolls, E.T., Grabenhorst, F., 2008. The orbitofrontal cortex and beyond: from affect to decision-making. Prog. Neurobiol. 86, 216–244.
Rolls, E.T., Grabenhorst, F., Parris, B.A., 2008a. Warm pleasant feelings in the brain. Neuroimage 41, 1504–1513.
Rolls, E.T., Grabenhorst, F., Parris, B., 2010. Neural systems underlying decisions about affective odors. J. Cogn. Neurosci. 10, 1068–1082.
Rolls, E.T., Kringelbach, M.L., de Araujo, I.E.T., 2003a. Different representations of pleasant and unpleasant odors in the human brain. Eur. J. Neurosci. 18, 695–703.
Rolls, E.T., McCabe, C., 2007. Enhanced affective brain representations of chocolate in cravers vs. non-cravers. Eur. J. Neurosci. 26, 1067–1076.
Rolls, E.T., McCabe, C., Redoute, J., 2008b. Expected value, reward outcome, and temporal difference error representations in a probabilistic decision task. Cereb. Cortex 18, 652–663.
Rolls, E.T., O'Doherty, J., Kringelbach, M.L., Francis, S., Bowtell, R., McGlone, F., 2003b. Representations of pleasant and painful touch in the human orbitofrontal and cingulate cortices. Cereb. Cortex 13, 308–317.
Rolls, E.T., Rolls, B.J., Rowe, E.A., 1983. Sensory-specific and motivation-specific satiety for the sight and taste of food and water in man. Physiol. Behav. 30, 185–192.
Rolls, E.T., Sienkiewicz, Z.J., Yaxley, S., 1989. Hunger modulates the responses to gustatory stimuli of single neurons in the caudolateral orbitofrontal cortex of the macaque monkey. Eur. J. Neurosci. 1, 53–60.
Royet, J.P., Plailly, J., Delon-Martin, C., Kareken, D.A., Segebarth, C., 2003. fMRI of emotional responses to odors: influence of hedonic valence and judgment, handedness, and gender. Neuroimage 20, 713–728.
Royet, J.P., Zald, D., Versace, R., Costes, N., Lavenne, F., Koenig, O., Gervais, R., 2000. Emotional responses to pleasant and unpleasant olfactory, visual, and auditory stimuli: a positron emission tomography study. J. Neurosci. 20, 7752–7759.
Seymour, B., O'Doherty, J.P., Dayan, P., Koltzenburg, M., Jones, A.K., Dolan, R.J., Friston, K.J., Frackowiak, R.S., 2004. Temporal difference models describe higher-order learning in humans. Nature 429, 664–667.
Wilson, J.L., Jenkinson, M., Araujo, I.E.T., Kringelbach, M.L., Rolls, E.T., Jezzard, P., 2002. Fast, fully automated global and local magnetic field optimisation for fMRI of the human brain. Neuroimage 17, 967–976.
Yaxley, S., Rolls, E.T., Sienkiewicz, Z.J., 1990. Gustatory responses of single neurons in the insula of the macaque monkey. J. Neurophysiol. 63, 689–700.
Zink, C.F., Pagnoni, G., Martin-Skurski, M.E., Chappelow, J.C., Berns, G.S., 2004. Human striatal responses to monetary reward depend on saliency. Neuron 42, 509–517.