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Selective attention to affective value alters how the brain processes taste stimuli

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Abstract

How does selective attention to affect influence sensory processing? In an fMRI investigation, when subjects were instructed to remember and rate the pleasantness of a taste stimulus, 0.1 M monosodium glutamate, activations were greater in the medial orbitofrontal and pregenual cingulate cortex than when subjects were instructed to remember and rate the intensity of the taste. When the subjects were instructed to remember and rate the intensity, activations were greater in the insular taste cortex. An interaction analysis showed that this dissociation of taste processing, depending on whether attention to pleasantness or intensity was relevant, was highly significant ($P < 0.0002$). Thus, depending on the context in which tastes are presented and whether affect is relevant, the brain responds to a taste differently. These findings show that, when attention is paid to affective value, the brain systems engaged to represent the sensory stimulus of taste are different from those engaged when attention is directed to the physical properties of a stimulus such as its intensity. This differential biasing of brain regions engaged in processing a sensory stimulus, depending on whether the cognitive demand is for affect-related vs. more sensory-related processing, may be an important aspect of cognition and attention. This has many implications for understanding the effects not only of taste but also of other sensory stimuli.

Introduction

The primary taste cortex in primates and humans is in the anterior insula (Scott *et al*., 1986, 1991; Rolls *et al*., 1988; Yaxley *et al*., 1988, 1990; Scott & Plata-Salaman, 1999; Small *et al*., 1999; O'Doherty *et al*., 2001; de Araujo *et al*., 2003a,c; Schoenfeld *et al*., 2004; Verhagen *et al*., 2004; Grabenhorst *et al*., 2007), and the exact insular and opercular cortex regions where taste neurons are recorded (Scott *et al*., 1986; Yaxley *et al*., 1990) project forward into the orbitofrontal cortex (Baylis *et al*., 1995) where taste neurons are found (Thorpe *et al*., 1983; Rolls *et al*., 1989, 1990, 1996, 2003b; Verhagen *et al*., 2003; Kadohisa *et al*., 2004; Rolls, 2006) and where in humans activations to taste are found (Small *et al*., 1999, 2004; O'Doherty *et al*., 2001; de Araujo *et al*., 2003c; Small & Prescott, 2005; Gottfried *et al*., 2006a; Grabenhorst *et al*., 2007; McCabe & Rolls, 2007). The orbitofrontal cortex has onward connections to the pregenual cingulate cortex (Carmichael & Price, 1996). In the insular primary taste cortex of macaques the neuronal taste responses are not hunger-dependent; that is, they do not represent the reward value of the taste, though they do reflect the concentration of the taste stimulus (Rolls *et al*., 1988; Yaxley *et al*., 1988). In the secondary taste cortex of macaques in the orbitofrontal cortex, most of the neuronal taste responses are hunger-dependent and so encode the reward value of the taste stimulus (Rolls *et al*., 1989, 1990, 1996; Rolls, 2006). Correspondingly, in humans the activations in the primary taste cortex are correlated with the rated subjective intensity of the taste stimulus, and those in the orbitofrontal cortex are correlated with the rated subjective pleasantness of the taste stimulus (Grabenhorst *et al*., 2007; Guest *et al*., 2007).

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These studies did not investigate effects of attention on taste processing. However, given that there are separate representations of different attributes of taste, including their intensity and pleasantness, it could be that within the taste modality selective attention to pleasantness might engage processing in some taste areas, and to intensity might activate other cortical areas. This could have very important implications: how we respond to tastes, and potentially other stimuli too, might depend on the instructions or the context in which the taste was delivered. In this investigation, this hypothesis was tested.

We note that top-down attention involves a modulation, probably by biased competition, of the responses of neurons to the incoming sensory stimuli (Desimone & Duncan, 1995; Rolls & Deco, 2002; Deco & Rolls, 2005a; Rolls, 2008). The effects of top-down modulation of affective vs. intensity processing for taste have not been investigated previously; some were found in this study, and could operate by mechanisms analogous to those of top-down attentional control, as described in the Discussion.

Materials and methods

Overall design

The hypotheses raised in the Introduction were investigated with the following task in an fMRI investigation. The identical taste stimulus, 0.1 M monosodium glutamate with 0.005 M inosine monophosphate (see de Araujo *et al*., 2003a), referred to throughout this paper for brevity as monosodium glutamate, was used in both trial types. A trial started 5 s before the taste delivery with the visual instruction either 'Remember and Rate Pleasantness' or 'Remember and Rate Intensity', which was shown until the end of the taste period. The taste period was from t = 0 s until t = 9 s, and in this period a red cross was also

present indicating that swallowing should not occur. The differences between the activations in this period were a measure of the top-down selective attention instructions while the taste was being delivered. After the end of the taste period the visual instruction and red cross were turned off, and a green cross was shown cueing the subject to swallow. After 2 s a tasteless rinse was delivered with a red cross, and the rinse period was from t = 11 until t = 18 s, when the green cross appeared to cue a swallow. After this the rating of pleasantness or intensity was made using button-press operated visual rating scales as described previously (Rolls *et al*., 2003a).

These two trial types, in which the instructions were to remember and rate either pleasantness or intensity, were those crucial to the present investigation and its hypotheses. They were interspersed in random permuted sequence with other trials that were part of a different investigation in which there was no pretrial instruction or attention period, and cognitive modulation by word labels of taste and flavour processing in the brain were being investigated (Grabenhorst *et al*., 2007). The tastes used on these other trials were monosodium glutamate at concentrations of 0.1 and 0.4 M, the flavours were 0.1 M monosodium glutamate and vegetable odour, and the word labels for the taste condition were 'Rich and delicious taste' or 'monosodium glutamate'. These other trials were helpful in the current investigation because they enabled brain regions where activations were correlated with the pleasantness of taste stimuli, or their intensity, to be localized. Each of the seven trial types was presented in random permuted sequence nine times. This general protocol and design has been used successfully in previous studies to investigate taste cortical areas (O'Doherty *et al*., 2001; de Araujo *et al*., 2003c; Grabenhorst *et al*., 2007; McCabe & Rolls, 2007). As seven trial types were being run in the scanner at the same time, and included different stimuli (Grabenhorst *et al*., 2007), and no instructions were given about the number of stimuli being used or that the stimuli were the same on the 'Remember and Rate Intensity' and 'Remember and Rate Pleasantness' trials, the participants simply had to concentrate on following the instructions about what aspect of the taste stimulus, intensity or pleasantness, had to be rated on that trial.

Participants

Twelve healthy volunteers (six male and six female, age range 21–35 years) participated in the study. Ethical approval (Central Oxford Research Ethics Committee) and written informed consent from all subjects were obtained before the experiment. the subjects had not eaten for three hours before the investigation.

Stimuli and stimulus delivery

The taste stimulus was monosodium glutamate (0.1 M monosodium glutamate and 0.005 M inosine monophosphate). We included a tasteless control solution containing the main ionic components of saliva (25 mM KCl plus 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 (O'Doherty *et al*., 2001; de Araujo *et al*., 2003a). 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 (O'Doherty *et al*., 2001; de Araujo *et al*., 2003a; de Araujo *et al*., 2003b). For the contrasts described in this paper such as 'Remember and rate pleasantness' – 'Remember and rate intensity', explicit subtraction of effects related to the rinse was not applied, as the rinse effect was common to each of the two conditions involved in the subtraction.

Stimuli were delivered to the subject's mouth through four Teflon tubes (one for each of the three taste or flavour stimuli, and a separate tube for the tasteless rinse control) which were held between the lips. Each Teflon tube of ~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.), which allowed 0.75 mL of any stimulus to be delivered at the time indicated by the computer.

fMRI 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 echo planar imaging (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 s). We used the techniques that we have developed over a number of years (O'Doherty *et al*., 2001; de Araujo *et al*., 2003a) and, as described in detail by Wilson *et al*. (2002), we carefully selected the imaging parameters in order to minimise 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 to −46 mm (anteroposterior). A whole-brain T2*-weighted EPI volume of the above dimensions and an anatomical T1 volume with coronal plane slice thickness 3 mm and in-plane resolution of 1 × 1 mm was also acquired.

fMRI data analysis

The imaging data were analysed using Statistical Parametric Mapping (SPM)5 (Wellcome Institute of Cognitive Neurology). Pre-processing of the data used SPM5 realignment, reslicing with sinc interpolation, normalization 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. Time-series non-sphericity at each voxel was estimated and corrected for (Friston *et al*., 2002), and a high-pass filter with a cutoff period of 128 s was applied. Because we were interested not only in the activations related to the delivery of taste but also in possible further analyses of activations that might be related to working memory in the period following the taste delivery on these trials, a finite impulse response (FIR) analysis was performed as implemented in SPM, in order to make no assumption about the time course based on the temporal filtering property of the haemodynamic response function (Henson, 2003; Gottfried *et al*., 2006b; Yacubian *et al*., 2006). We used 16 delta functions in the FIR analysis, spaced at intervals of the TR (2 s) and starting 2 s before the onset of the visual cue at time −5 s instructing the subject to 'Remember and rate pleasantness' (or intensity) on that trial. This basis set considers each time bin after stimulus onset individually to model the blood oxygen level-dependent (BOLD) response and can capture any possible shape of response function up to a given frequency limit. In this model, the parameter estimate for each time bin represents the average BOLD response at that time. These parameter estimates are directly proportional to the BOLD signal. Data were analysed statistically for each subject individually (first-level

analysis) and for the group (second-level analysis). At the single-subject level, the parameter estimate maps for the FIR analysis for the time delays at which taste-related activations were expected were estimated (in our case, the FIR values for times starting 6 and 8 s after taste delivery were used, and are consistent with the haemodynamic delays inherent in the BOLD response; Henson, 2003). Following smoothness estimation (Kiebel *et al*., 1999), linear contrasts of parameter estimates were defined to test the specific effects of each condition with each individual dataset. Voxel values for each contrast resulted in a statistical parametric map of the corresponding *t*-statistic, which was then transformed into the unit normal distribution (SPM *z*). The statistical parametric maps from each individual dataset were then entered into second-level random-effects analyses accounting for both scan-to-scan and subject-to-subject variability. More precisely, the sets of individual statistical maps corresponding to a specific effect of interest were entered as covariates in multiple regression models as implemented in SPM5, and the corresponding group effects were assessed by applying linear contrasts (again following smoothness estimation) to the (second-level) parameter estimates generating a *t*-statistics map for each group effect of interest. The SPM contrast analyses performed tested for a difference between paying attention to pleasantness vs. intensity and vice versa. We report results for brain regions where there were specific prior hypotheses based on taste-related activation described in previous studies, including parts of the orbitofrontal and anterior cingulate cortex, and insula, in which we and others have found activations to taste (O'Doherty *et al*., 2001; de Araujo *et al*., 2003a,c; Schoenfeld *et al*., 2004; Grabenhorst *et al*., 2007; McCabe & Rolls, 2007) and applied small-volume corrections for multiple comparisons (Worsley *et al*., 1996) with a radius corresponding to the full width at half maximum of the spatial smoothing filter used. Peaks are reported for which $P < 0.05$ corrected for false discovery rate, though the actual corrected probability values (Worsley *et al*., 1996) are given in the text.

The correlation analyses of the fMRI BOLD 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 *t*-maps resulting from performing linear parametric modulation as implemented in SPM5. For voxels where significant correlations were found between the percentage BOLD signal and the ratings, we produced graphs to show how the ratings were related to the percentage BOLD signal. These were produced for each subject by taking the average of the BOLD response in the three time bins at 4, 6 and 8 s after the delivery of the taste 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.

Results

Effects of attention to pleasantness during taste delivery

A contrast for the condition 'Remember and rate pleasantness' vs. 'Remember and rate intensity' for the taste period (FIRs taken at 6 and 8 s after the onset of taste delivery) revealed a significant difference in the medial orbitofrontal cortex at coordinates [mediolateral −6, anteroposterior 14, dorsoventral −20 mm]: $z = 3.81$, $P < 0.003$; and in the pregenual cingulate cortex at [−4, 46, −8]: $z = 2.90$, $P < 0.04$, as shown in Fig. 1 (top). Figure 1 (middle right) shows the parameter estimates (mean ± SEM across subjects) for the activation in the medial orbitofrontal cortex for the conditions of paying attention to pleasantness or to intensity. The parameter estimates were significantly different ($t_{11} = 7.27$, $P < 10^{-4}$). Figure 1 (middle left) shows that at this location in the medial orbitofrontal cortex there was a correlation between the subjective pleasantness ratings and the activation (% BOLD change; $r_8 = 0.94$, $P << 0.001$). (The taste stimulus for the correlation analyses was 0.1 M monosodium glutamate on all trials, but was accompanied on some trials by the label 'Rich and delicious taste' and on other trials by the label 'monosodium glutamate'.) There was no significant correlation with the intensity ratings in this brain region in the SPM correlation analysis (using the same stimuli described below for the insula, where there was a correlation with the intensity ratings).

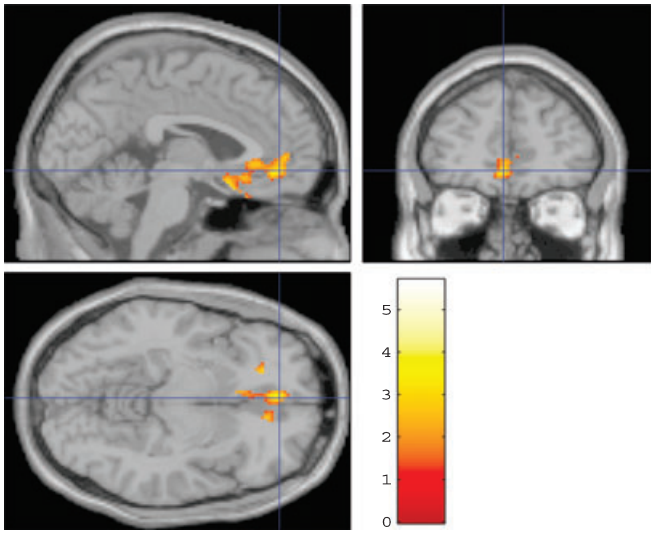
Figure 1 (bottom) shows the findings for the pregenual cingulate cortex. The parameter estimates (bottom right) were significantly different for the condition 'Remember and rate pleasantness' vs. 'Remember and rate intensity' ($t_{11} = 8.70$, $P < 10^{-5}$). Figure 1 (bottom left) shows that at this location there was a correlation between the pleasantness ratings and the activation (% BOLD change: $r_8 = 0.89$, $P = 0.001$). There was no significant correlation with the intensity ratings in this brain region in the SPM correlation analysis (using the same stimuli described below for the insula, where there was a correlation with the intensity ratings).

The results thus show that activations related to taste delivery were larger in the medial orbitofrontal cortex and pregenual cingulate cortex when attention was being paid to the pleasantness as opposed to the intensity of the tastant. No significant differences were found in the anterior part of the insula (between Talairach $y = 6$ and $y = 22$) where taste stimuli with a tasteless rinse subtracted have been shown in previous studies to produce activations (O'Doherty *et al*., 2001; de Araujo *et al*., 2003a,c; Schoenfeld *et al*., 2004; Grabenhorst *et al*., 2007). Further, the results show that the regions of the medial orbitofrontal cortex and pregenual cingulate cortex where attention to pleasantness selectively increased activations to the taste stimulus were regions where the pleasantness of the stimuli was represented, as shown by the correlations with the subjective ratings of the pleasantness of taste stimuli.

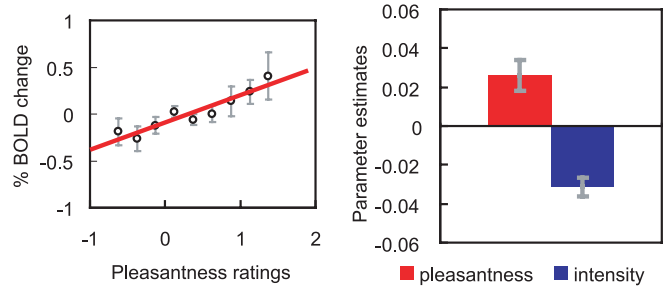
Effects of attention to intensity during taste delivery

A contrast for the condition 'Remember and rate intensity' vs. 'Remember and rate pleasantness' for the taste period (FIRs taken at 6 and 8 s after the onset of taste delivery) revealed a significant difference in the taste insula at [42, 18, −14]: $z = 2.42$, $P < 0.05$; and in the mid insula at [40, −2, 4]: $z = 3.03$, $P < 0.025$, as shown in Fig. 2 (top). Figure 2 (middle right) shows the parameter estimates (mean ± SEM across subjects) for the activation in the taste insula for the conditions of paying attention to pleasantness or to intensity. The parameter estimates were significantly different ($t_{10} = 4.5$, $P = 0.001$). Figure 2 (middle left) shows that at this location in the taste insula there was a correlation between the subjective intensity ratings and the activation (% BOLD change: $r_{14} = 0.91$, $P < 0.001$). (The taste stimuli for these correlation analyses were 0.1 and 0.4 M monosodium glutamate on all trials, accompanied by the label 'monosodium glutamate'.)

Figure 2 (bottom) shows the findings for the mid-insular cortex. The parameter estimates (bottom right) were significantly different for the condition 'Remember and rate pleasantness' vs. 'Remember and rate intensity' ($t_{10} = 5.02$, $P = 0.001$). Figure 2 (bottom left) shows that at this location there was a correlation between the intensity ratings and the activation (% BOLD change: $r_{15} = 0.89$, $P << 0.001$). There were no correlations at either of the insular sites with the ratings of pleasantness calculated as described above.



Medial orbitofrontal cortex



Pregenual cingulate cortex

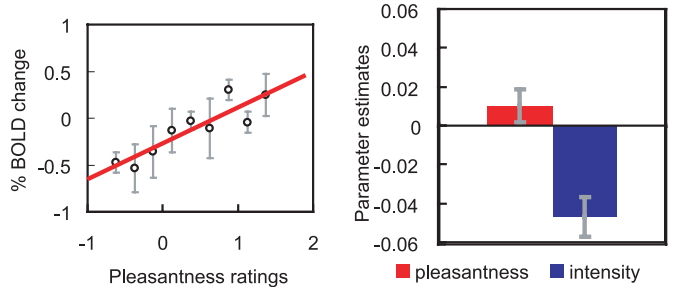
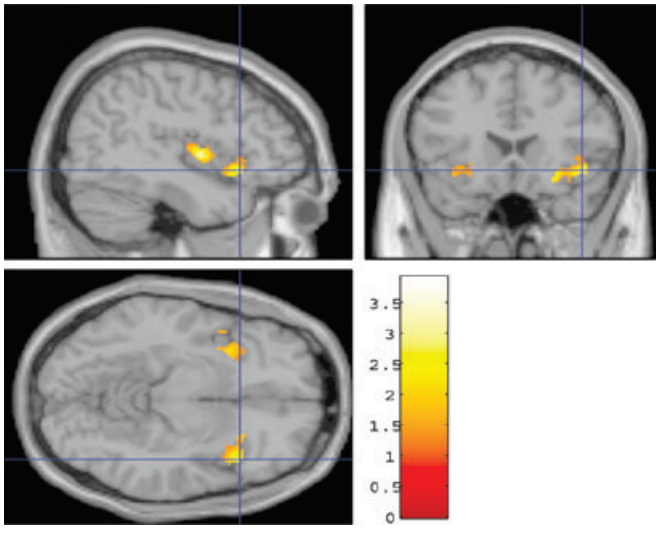
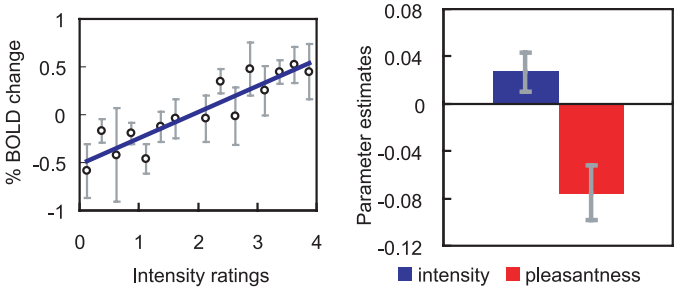


FIG. 1. Taste period: effect of paying attention to pleasantness as opposed to intensity. (Top) A significant difference related to the taste period was found in the medial orbitofrontal cortex at [−6, 14, −20]: $z = 3.81$, $P < 0.003$ (towards the back of the area of activation shown) and in the pregenual cingulate cortex at [−4, 46, −8]: $z = 2.90$, $P < 0.04$ (at the cursor). (Middle) Medial orbitofrontal cortex. (Right) The parameter estimates (mean ± SEM across subjects) for the activation at the specified coordinate for the conditions of paying attention to pleasantness or to intensity. The parameter estimates were significantly different for the orbitofrontal cortex: $t_{11} = 7.27$, $P < 10^{-4}$. (Left) The correlation between the pleasantness ratings and the activation (% BOLD change) at the specified coordinate ($r_8 = 0.94$, $P << 0.001$). (Bottom) Pregenual cingulate cortex. Conventions as above. (Right) The parameter estimates were significantly different for the pregenual cingulate cortex: $t_{11} = 8.70$, $P < 10^{-5}$. (Left) The correlation between the pleasantness ratings and the activation (% BOLD change) at the specified coordinate ($r_8 = 0.89$, $P = 0.001$). The taste stimulus, monosodium glutamate, was identical on all trials.



Taste insula



Mid-insula

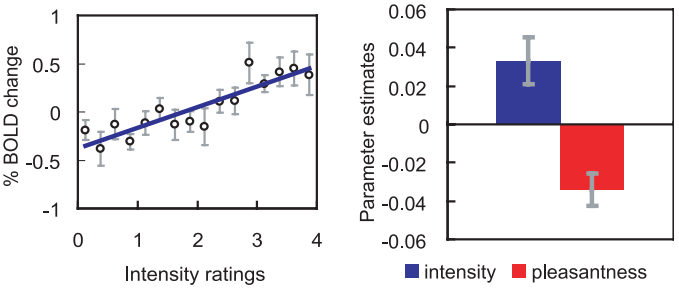


FIG. 2. Taste period: effect of paying attention to intensity as opposed to pleasantness. (Top) A significant difference related to the taste period was found in the taste insula at [42, 18, −14]: $z = 2.42$, $P < 0.05$ (indicated by the cursor) and in the mid insula at [40, −2, 4]: $z = 3.03$, $P < 0.025$. (Middle) Taste insula. (Right) The parameter estimates (mean ± SEM across subjects) for the activation at the specified coordinate for the conditions of paying attention to pleasantness or to intensity. The parameter estimates were significantly different for the taste insula: $t_{10} = 4.5$, $P = 0.001$. (Left) The correlation between the intensity ratings and the activation (% BOLD change) at the specified coordinate ($r_{14} = 0.91$, $P << 0.001$). (Bottom) Mid-insula. (Right) The parameter estimates (mean ± SEM across subjects) for the activation at the specified coordinate for the conditions of paying attention to pleasantness or to intensity. The parameter estimates were significantly different for the mid-insula: $t_{10} = 5.02$, $P = 0.001$. (Left) The correlation between the intensity ratings and the activation (% BOLD change) at the specified coordinate ($r_{15} = 0.89$, $P << 0.001$). The taste stimulus, monosodium glutamate, was identical on all trials. Conventions as in Fig. 1.

The results thus show that activations related to taste delivery were larger in the taste insula and mid-insula when attention was being paid to the intensity as opposed to the pleasantness of the tastant. Further, the regions of the taste insular cortex and mid-insular cortex where attention to intensity selectively increased activations to the taste stimulus were regions where the intensities of the stimuli was represented, as shown by the correlations with the subjective ratings of the intensity of taste stimuli.

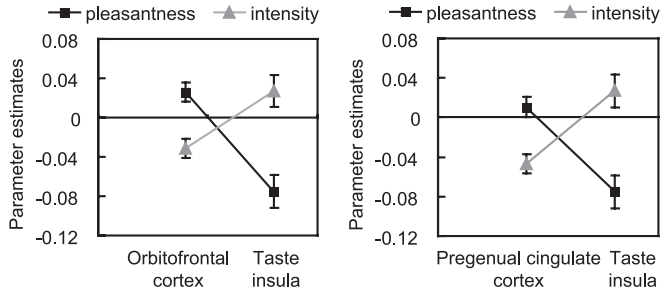


FIG. 3. The effect of paying attention to taste pleasantness as opposed to intensity produced highly significant interactions based on the parameter estimates of the activations in the orbitofrontal cortex vs. insular taste cortex (left, $P < 0.0002$), and in the pregenual cingulate vs. insular taste cortex (right, $P < 0.0001$). The means ± SEM of the parameter estimates from the SPM analysis are shown (see text). The coordinates of the orbitofrontal cortex region (that shown in Fig. 1) were [−6, 14, −20]. The coordinates of the pregenual cingulate cortex region (also shown in Fig. 1) were [−4, 46, −8]. The coordinates of the taste insular cortex region (that shown in Fig. 2) were [42, 18, −14].

Dissociation between activations in different brain areas when paying attention to pleasantness and when paying attention to intensity

To test statistically whether there was a dissociation between the brain areas where paying attention to pleasantness vs. paying attention to intensity increased the activations to the taste stimulus, we performed ANOVAs on the parameter estimates (obtained from the statistically significant SPM analyses with FIRs at 6 and 8 s as described above), where one factor was the attention condition and the other factor was the brain area. The interaction was significant for, for example, the medial orbitofrontal cortex vs. taste insula (interaction $F_{1,10} = 34.12$, $P < 0.0002$) and for the pregenual cingulate cortex vs. the taste insula (interaction $F_{1,10} = 39.15$, $P < 0.0001$; see Fig. 3). The implication is that paying attention to pleasantness increased activations selectively in the medial orbitofrontal cortex and pregenual cingulate cortex relative to the insula, and that paying attention to intensity increased activations in the taste insula relative to the medial orbitofrontal cortex and pregenual cingulate cortex.

Discussion

The results show that to what attribute of the stimulus attention is being paid, its pleasantness or its intensity, can have profound influences on how different brain regions respond to a taste. These effects are found both within and beyond the primary taste cortex. In the primary taste cortex, when the selective attention instruction was 'Remember and rate intensity', activations were larger than when the instruction was 'Remember and rate pleasantness' (Fig. 2). In contrast, in the medial orbitofrontal cortex and pregenual cingulate cortex, there was more activation when the selective attention instruction was 'Remember and rate pleasantness' than when the instruction was 'Remember and rate intensity' (Fig. 1). This is not just a general effect of attention or arousal, in that the comparison is not to a baseline condition in which tastes were delivered without any instruction to pay attention. Instead, the effect is one of selective attention, in which attention is being paid on both types of trial, but to either pleasantness or intensity. Moreover, the effects found (in the anterior insula, orbitofrontal cortex and pregenual cingulate cortex) were found in brain regions shown in previous investigations to be activated by taste stimuli such as 0.1 M monosodium glutamate – tasteless control, and 1 M glucose – tasteless control (de Araujo *et al*., 2003a).

These results are of considerable interest, for they show that the way in which the brain processes taste stimuli depends on exactly what instructions are given. Thus the task instructions, or more generally environmental context, can influence how brain areas process tastes with respect to affective value, and taking this into account is likely to have important implications for understanding the effects produced by sensory stimuli, not only in the laboratory but also in daily life.

It was also of considerable interest that the brain areas where instructions to pay attention to pleasantness vs. intensity increased the activations (the medial orbitofrontal cortex and pregenual cingulate cortex) were brain regions where the processing is of affective value, as shown by the finding of a correlation with subjective taste pleasantness ratings but not subjective taste intensity ratings in these regions. In contrast, the brain areas where instructions to pay attention to intensity vs. pleasantness increased the activations (e.g. the insular taste cortex) were brain regions where the processing is primarily of intensity and the identity of the taste stimulus, as shown by the finding of a correlation with subjective taste intensity ratings but not subjective taste pleasantness ratings in the insular taste cortex. (The identity of a taste is represented in the primary, anterior insular, taste cortex of macaques in that neurons in this region are tuned with preferences for the different tastes sweet, salt, bitter, sour and umami (Scott *et al*., 1986; Yaxley *et al*., 1990; Baylis & Rolls, 1991; Scott & Plata-Salaman, 1999). Although of course these taste stimuli have different reward values, reward value does not appear to be made explicit in the representation of single neurons in this region in macaques, in that these neurons do not decrease their response to a sweet taste when it is fed to normal self-determined satiety (Rolls *et al*., 1988; Yaxley *et al*., 1988). The important conclusion from this is that not only is taste pleasantness processed in separate regions from taste intensity, allowing separate outputs to behaviour from these different types of processing (Rolls *et al*., 1989; Small *et al*., 2003; Rolls, 2005, 2007, 2008; Grabenhorst *et al*., 2007), but also the selective top-down attentional effects modulate the activations in the appropriate areas, namely in the insula for intensity and the medial orbitofrontal cortex and pregenual cingulate cortex for pleasantness.

The top-down attentional influence of the task instructions can be envisaged as modulating the bottom-up (i.e. sensory input) responses of different brain regions to process in different ways the taste being delivered. The top-down influence is understood in many brain systems to operate by biased competition (Duncan & Humphreys, 1989; Desimone & Duncan, 1995; Chelazzi *et al*., 2001; Rolls & Deco, 2002; Rolls, 2008). In this biased competition model (which is now able at the integrate-and-fire neuron level of implementation to account for nonlinear effects of top-down attention; Deco & Rolls, 2005b), a relatively weak top-down input can bias how a population of neurons responds to a sensory input, and different top-down signals (instructions in the present experiment) can bias different populations of neurons so that they, rather than unbiased populations, win the competition when the stimulus appears. We hypothesize that this mechanism underlies the effects described here, with the top-down bias specifically selecting areas and neurons involved in processing affective value vs. stimulus intensity. Further, the top-down cognitive effects produced by a word label which influences affective value but not intensity show similar selectivity, in that when a particular taste (the 0.1 M monosodium glutamate used in the present study) is described as 'Rich and delicious' as opposed to 'monosodium glutamate' there is enhanced activation in the medial orbitofrontal and pregenual cingulate cortex, but not in the insular taste cortex (Grabenhorst *et al*., 2007).

There have been few previous studies of the role of attention on the brain processing of tastes. However, in one study participants were

instructed to try to detect whether a taste was present (vs. trials in which the instruction was to randomly press a button in the response period, so that the design did not encompass selective attention to different aspects of a taste), and this produced more activation of the anterior insular cortex (Veldhuizen *et al*., 2007). This finding is consistent with the present finding, for in that experiment the instruction directed attention to the physical aspects of the stimulus (whether a taste was present), and this influenced activations in the insular taste cortex.

Top-down attentional effects that bias processing between brain regions depending on whether the instruction is to pay attention to pleasantness vs. intensity may well, we suggest, apply to other modalities, and indeed analogous effects have been found for olfactory stimuli (Rolls *et al*., 2008). Further, modulation of activations in regions such as the orbitofrontal and pregenual cingulate cortex that represent affective value are found when the pleasantness of olfactory (de Araujo *et al*., 2005), taste (Grabenhorst *et al*., 2007), flavour (Grabenhorst *et al*., 2007) and somatosensory (McCabe *et al*., 2008) stimuli is modulated by a top-down word label that describes the pleasantness of the stimuli, with much less evident effects in earlier cortical processing areas. Top-down attentional effects in vision, to bias processing with respect to, for example, particular locations or particular objects, have been extensively described, and the mechanisms are becoming understood (Duncan & Humphreys, 1989; Desimone & Duncan, 1995; Chelazzi *et al*., 2001; Rolls & Deco, 2002; Deco & Rolls, 2005b; Rolls, 2008).

Similar effects to those found in the anterior insula were also found in this investigation in a mid-insula region (at $y = -2$). Although in many studies it is the anterior insula (in a region between $y \approx 22$ and $y \approx 6$) that responds to taste stimuli (de Araujo *et al*., 2003a; Grabenhorst *et al*., 2007; McCabe & Rolls, 2007) and which may be the human primary taste cortex corresponding to the insular and opercular primary taste cortex of macaques (Pritchard *et al*., 1986; Scott *et al*., 1986; Rolls *et al*., 1988; Yaxley *et al*., 1988, 1990; Kadohisa *et al*., 2005; Rolls, 2007), activations to taste stimuli have been found in some more mid-insular areas in a number of studies (Small *et al*., 2003; Veldhuizen *et al*., 2007). This mid-insular area is also involved in representing oral texture (de Araujo *et al*., 2003b; de Araujo & Rolls, 2004) and temperature (Guest *et al*., 2007), so it is an oral somatosensory region that could also have some taste inputs.

These findings show that, when attention is paid to the affective value of a taste, the brain systems engaged to represent the sensory stimulus are different from those engaged when attention is directed to the physical properties, such as intensity, of the identical stimulus. The findings are supported by other findings that when attention is paid to the affective value of an odour, the brain systems engaged to prepare for, represent and remember that sensory stimulus are different from those engaged when attention is directed to the physical properties, such as intensity, of the identical stimulus (Rolls *et al*., 2008). This differential biasing of brain regions engaged in processing a sensory stimulus depending on whether the cognitive demand is for affect-related or for more sensory-related processing may apply to a number of different sensory modalities, and may be an important aspect of cognition and attention.

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Abbreviations

BOLD, blood oxygen level-dependent; coordinates, [mediolateral, anteroposterior, dorsoventral], in mm; FIR, finite impulse response; SPM, Statistical Parametric Mapping.

References

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., Kringelbach, M.L., Rolls, E.T. & McGlone, F. (2003b) Human cortical responses to water in the mouth, and the effects of thirst. *J. Neurophysiol.*, **90**, 1865–1876.

de Araujo, I.E.T. & Rolls, E.T. (2004) The representation in the human brain of food texture and oral fat. *J. Neurosci.*, **24**, 3086–3093.

de Araujo, I.E.T., Rolls, E.T., Kringelbach, M.L., McGlone, F. & Phillips, N. (2003c) Taste-olfactory convergence, and the representation of the pleasantness of flavour, in the human brain. *Eur. J. Neurosci.*, **18**, 2374–2390.

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.

Baylis, L.L. & Rolls, E.T. (1991) Responses of neurons in the primate taste cortex to glutamate. *Physiol. Behav.*, **49**, 973–979.

Baylis, L.L., Rolls, E.T. & Baylis, G.C. (1995) Afferent connections of the orbitofrontal cortex taste area of the primate. *Neuroscience*, **64**, 801–812.

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.

Chelazzi, L., Miller, E.K., Duncan, J. & Desimone, R. (2001) Responses of neurons in macaque area V4 during memory-guided visual search. *Cereb. Cortex*, **11**, 761–772.

Collins, D.L., Neelin, P., Peters, T.M. & Evans, A.C. (1994) Automatic 3D intersubject registration of MR volume tric data in standardized Talairach space. *J. Comput. Assist. Tomogr.*, **18**, 192–205.

Deco, G. & Rolls, E.T. (2005a) Attention, short-term memory, and action selection: a unifying theory. *Prog. Neurobiol.*, **76**, 236–256.

Deco, G. & Rolls, E.T. (2005b) Neurodynamics of biased competition and co-operation for attention: a model with spiking neurons. *J. Neurophysiol.*, **94**, 295–313.

Desimone, R. & Duncan, J. (1995) Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.*, **18**, 193–222.

Duncan, J. & Humphreys, G.W. (1989) Visual search and stimulus similarity. *Psychol. Rev.*, **96**, 433–458.

Friston, K.J., Glaser, D.E., Henson, R.N., Kiebel, S., Phillips, C. & Ashburner, J. (2002) Classical and Bayesian inference in neuroimaging: applications. *Neuroimage*, **16**, 484–512.

Gottfried, J.A., Small, D.M. & Zald, D.H. (2006a) The chemical senses. In Zald, D.H. & Rauch, S.L. (eds), *The Orbitofrontal Cortex*. Oxford University Press, Oxford, pp. 125–171.

Gottfried, J.A., Winston, J.S. & Dolan, R.J. (2006b) Dissociable codes of odor quality and odorant structure in human piriform cortex. *Neuron*, **49**, 467–479.

Grabenhorst, F., Rolls, E.T. & Bilderbeck, A. (2007) How cognition modulates affective responses to taste and flavor: top down influences on the orbitofrontal and pregenual cingulate cortices. *Cereb. Cortex*, in press. [doi: 10.1093/cercor/bhm185]

Guest, S., Grabenhorst, F., Essick, G., Chen, Y., Young, M., McGlone, F., de Araujo, I. & Rolls, E.T. (2007) Human cortical representation of oral temperature. *Physiol. Behav.*, **92**, 975–984.

Henson, R. (2003) Analysis of fMRI time series. In Ashburner, J., Friston, K. & Penny, W. (eds). *Human Brain Function*. Academic Press, London.

Kadohisa, M., Rolls, E.T. & Verhagen, J.V. (2004) Orbitofrontal cortex neuronal representation of temperature and capsaicin in the mouth. *Neuroscience*, **127**, 207–221.

Kadohisa, M., Rolls, E.T. & Verhagen, J.V. (2005) Neuronal representations of stimuli in the mouth: the primate insular taste cortex, orbitofrontal cortex, and amygdala. *Chem. Senses*, **30**, 401–419.

Kiebel, S.J., Poline, J.B., Friston, K.J., Holmes, A.P. & Worsley, K.J. (1999) Robust smoothness estimation in statistical parametric maps using standardized residuals from the general linear model. *Neuroimage*, **10**, 756–766.

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 representation of touch in the human brain. *Social Cogn. Affect. Neurosci.*, in press

O'Doherty, J., Rolls, E.T., Francis, S., Bowtell, R. & McGlone, F. (2001) The representation of pleasant and aversive taste in the human brain. *J. Neurophysiol.*, **85**, 1315–1321.

Pritchard, T.C., Hamilton, R.B., Morse, J.R. & Norgren, R. (1986) Projections of thalamic gustatory and lingual areas in the monkey, Macaca fascicularis. *J. Comp. Neurol.*, **244**, 213–228.

Rolls, E.T. (2005) *Emotion Explained*. Oxford University Press, Oxford.

Rolls, E.T. (2006) Brain mechanisms underlying flavour and appetite. *Phil. Trans. Roy. Soc. Lond. B*, **361**, 1123–1136.

Rolls, E.T. (2007) Sensory processing in the brain related to the control of food intake. *Proc. Nutrition 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., Critchley, H.D., Mason, R. & Wakeman, E.A. (1996) Orbitofrontal cortex neurons: role in olfactory and visual association learning. *J. Neurophysiol.*, **75**, 1970–1981.

Rolls, E.T. & Deco, G. (2002) *Computational Neuroscience of Vision*. Oxford University Press, Oxford.

Rolls, E.T., Grabenhorst, F., Margot, C., da Silva, M.A.A.P. & Velazco, M.I. (2008) Selective attention to affective value alters how the brain processes olfactory stimuli. *J. Cogn. Neurosci.*, in press.

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., Scott, T.R., Sienkiewicz, Z.J. & Yaxley, S. (1988) The responsiveness of neurones in the frontal opercular gustatory cortex of the macaque monkey is independent of hunger. *J. Physiol. (Lond.)*, **397**, 1–12.

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.

Rolls, E.T., Verhagen, J.V. & Kadohisa, M. (2003b) Representations of the texture of food in the primate orbitofrontal cortex: neurons responding to viscosity, grittiness and capsaicin. *J. Neurophysiol.*, **90**, 3711–3724.

Rolls, E.T., Yaxley, S. & Sienkiewicz, Z.J. (1990) Gustatory responses of single neurons in the caudolateral orbitofrontal cortex of the macaque monkey. *J. Neurophysiol.*, **64**, 1055–1066.

Schoenfeld, M.A., Neuer, G., Tempelmann, C., Schussler, K., Noesselt, T., Hopf, J.M. & Heinze, H.J. (2004) Functional magnetic resonance tomography correlates of taste perception in the human primary taste cortex. *Neuroscience*, **127**, 347–353.

Scott, T.R. & Plata-Salaman, C.R. (1999) Taste in the monkey cortex. *Physiol. Behav.*, **67**, 489–511.

Scott, T.R., Plata-Salaman, C.R., Smith, V.L. & Giza, B.K. (1991) Gustatory neural coding in the monkey cortex: stimulus intensity. *J. Neurophysiol.*, **65**, 76–86.

Scott, T.R., Yaxley, S., Sienkiewicz, Z.J. & Rolls, E.T. (1986) Gustatory responses in the frontal opercular cortex of the alert cynomolgus monkey. *J. Neurophysiol.*, **56**, 876–890.

Small, D.M., Gregory, M.D., Mak, Y.E., Gitelman, D., Mesulam, M.M. & Parrish, T. (2003) Dissociation of neural representation of intensity and affective valuation in human gustation. *Neuron*, **39**, 701–711.

Small, D.M. & Prescott, J. (2005) Odor/taste integration and the perception of flavor. *Exp. Brain Res.*, **166**, 345–357.

Small, D.M., Voss, J., Mak, Y.E., Simmons, K.B., Parrish, T. & Gitelman, D. (2004) Experience-dependent neural integration of taste and smell in the human brain. *J. Neurophysiol.*, **92**, 1892–1903.

Small, D.M., Zald, D.H., Jones-Gotman, M., Zatorre, R.J., Pardo, J.V., Frey, S. & Petrides, M. (1999) Human cortical gustatory areas: a review of functional neuroimaging data. *Neuroreport*, **10**, 7–14.

Thorpe, S.J., Rolls, E.T. & Maddison, S. (1983) Neuronal activity in the orbitofrontal cortex of the behaving monkey. *Exp. Brain Res.*, **49**, 93–115.

Veldhuizen, M.G., Bender, G., Constable, R.T. & Small, D.M. (2007) Trying to detect taste in a tasteless solution: modulation of early gustatory cortex by attention to taste. *Chem. Senses*, **32**, 569–581.

Verhagen, J.V., Kadohisa, M. & Rolls, E.T. (2004) The primate insular/opercular taste cortex: neuronal representations of the viscosity, fat texture, grittiness, temperature and taste of foods. *J. Neurophysiol.*, **92**, 1685–1699.

Verhagen, J.V., Rolls, E.T. & Kadohisa, M. (2003) Neurons in the primate orbitofrontal cortex respond to fat texture independently of viscosity. *J. Neurophysiol.*, **90**, 1514–1525.

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.

Worsley, K.J., Marrett, P., Neelin, A.C., Friston, K.J. & Evans, A.C. (1996) A unified statistical approach for determining significant signals in images of cerebral activation. *Hum. Brain Mapp.*, **4**, 58–73.

Yacubian, J., Glascher, J., Schroeder, K., Sommer, T., Braus, D.F. & Buchel, C. (2006) Dissociable systems for gain- and loss-related value predictions and errors of prediction in the human brain. *J. Neurosci.*, **26**, 9530–9537.

Yaxley, S., Rolls, E.T. & Sienkiewicz, Z.J. (1988) The responsiveness of neurons in the insular gustatory cortex of the macaque monkey is independent of hunger. *Physiol. Behav.*, **42**, 223–229.

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.