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Representation of Sweet and Salty Taste Intensity in the Brain

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Abstract

The intensity of the taste of a food is affected mostly by the amount of sugars (mono- and disaccharides) or salt it contains. To season savory-tasting foods mainly table salt (NaCl) is used and to sweeten foods, sugars like sucrose are used. Foods with highly intense tastes are consumed in smaller amounts. The optimal taste intensity of a food is the intensity at which it is perceived as most pleasant. When taste intensity decreases or increases from optimal, the pleasantness of a food decreases. Here, we investigated the brain representation of sweet and salty taste intensity using functional magnetic resonance imaging. Fifteen subjects visited twice and tasted a range of 4 watery solutions (0–1 M) of either sucrose or NaCl in water. Middle insula activation increased with increasing concentration for both NaCl and sucrose. Despite similar subjective intensity ratings, anterior insula activation by NaCl increased more with concentration than that by sucrose. Amygdala activation increased with increasing NaCl concentration but not sucrose concentration. In conclusion, sweet and salty taste intensity are represented in the middle insula. Amygdala activation is only modulated by saltiness. Further research will need to extrapolate these results from simple solutions to real foods.

Key words: amygdala, functional MRI, insula, intensity

Introduction

The interplay between taste function and food intake is an important research area, of particular interest recently (Garcia-Bailo et al. 2009), due to the increase of obesity in the western world. Sensory properties of eaten foods influence the tasting process and thereby food intake (Sorensen et al. 2003). Major factors that affect satiation and thereby meal size are related to the degree of orosensory stimulation and include oral exposure time (de Wijk et al. 2008; Weijzen et al. 2009; Zijlstra et al. 2009), sensory complexity of the food (Weijzen et al. 2008; Ruijschop et al. 2010), and taste intensity (Vickers and Holton 2001). Taste intensity of a food depends strongly on sugar (mono- and disaccharides) and salt (NaCl) content: these are the 2 main types of seasoning agents. Savory foods are mainly seasoned with table salt (NaCl) and sweet foods contain sugars (often sucrose). Foods with highly intense tastes are consumed in smaller amounts (Vickers and Holton 2001), possibly due to a high degree of sensory-specific satiation. Taste intensity, that is, sweetness or saltiness, is tightly coupled to pleasantness (Veldhuizen et al. 2006). When intensity deviates from the (subjective) optimum, pleasantness declines.

The neurological processes underlying the perception of different food properties are still relatively unclear. The 5 basic tastes, the intensity and the affective value are a part of the gustatory pathway in the brain (Small 2006). So far, only one study has investigated the representation of taste intensity in the brain, using a low and a high concentration of a sweet (pleasant) and a bitter (unpleasant) taste in a 2×2 design (Small et al. 2003). In this study, it was found that the cerebellum, pons, putamen, middle insula, and amygdala respond to differences in taste intensity (Small et al. 2003). Here, we aim to reproduce these results for sweetness and extend them to saltiness. In addition, we aim to refine previous findings by employing a range of intensities rather than 2 extremes. Thus, our objective was to determine the brain regions where taste activation covaries with sweet and salty taste intensity.

Materials and methods

Subjects

Subjects were recruited with flyers posted at the University Medical Center Utrecht. After applying, subjects were invited for a screening session. During the screening, they rated all taste stimuli used in the experiment. This was done to verify that subjects could discriminate concentration differences. Subjects also completed a medical questionnaire and the restrained eating part of the Dutch Eating Behavior Questionnaire (Van Strien et al. 1986). Exclusion criteria included smoking, dieting for weight loss or having a medically prescribed diet, restrained eating (Van Strien 1997), use of medication and having an eating disorder, a history of or current alcohol consumption >28 units per week, or any medical diseases (including taste and smell disorders). Fifteen normal-weight right-handed men (mean age 23.3 ± 1.7 years, mean body mass index 22.0 ± 1.5 kg/m^2) participated. All experimental procedures were approved by the Medical Ethical Committee of the University Medical Center Utrecht and written informed consent was obtained from all subjects before the experiment. Data from one subject were not included in the analyses because of motion artifacts.

Functional magnetic resonance imaging paradigm

This study is a randomized crossover design study with 2 taste conditions; sweetness (sucrose) and saltiness (NaCl). There were 2 scan sessions, one per taste condition, on separate days at least 1 week apart. The order of the 2 scans was randomized across subjects. Subjects fasted for at least 2 h before the scan sessions (no food or beverage except water). During the functional run, subjects tasted 4 concentrations of sucrose or NaCl dissolved in water, with concentrations of 0, 0.13, 0.50, and 1.0 M and resulting intensities from ''zero'' to ''high.'' The 4 stimuli were pseudorandomly presented, 7 times each. After tasting 1 mL for 9 s, subjects either rated the intensity and pleasantness of a stimulus on visual analog scales (VAS duration 9 s, after 4 of 7 trials) or were directly cued on a screen to swallow (3 s). Subsequently, subjects received a rinse with water (9 s), followed again by a cue to swallow (3 s) and ''rest'' (fixation on a crosshair for 4 s). This is depicted in Figure 1. Inside the scanner, subjects held the tips of 5 bound flexible tubes in their mouth (diameter of 3 mm per tube). The tips where positioned comfortably between the lips such that the tubes delivered the stimuli on the front of the tongue. All stimuli and water (for rinsing) were administered at room temperature (23 °C) by use of 5 programmable syringe pumps (NE-500; New Era Pump Systems). The pumps were programmed to administer 1 mL of solution in 2.5 s. Also, VAS ratings of intensity and pleasantness were made during the scan by use of a custom-built button box. Instructions were displayed on a screen through a computer interface, run by the computer program PRESENTATION (Neurobehavioral Systems Inc.).

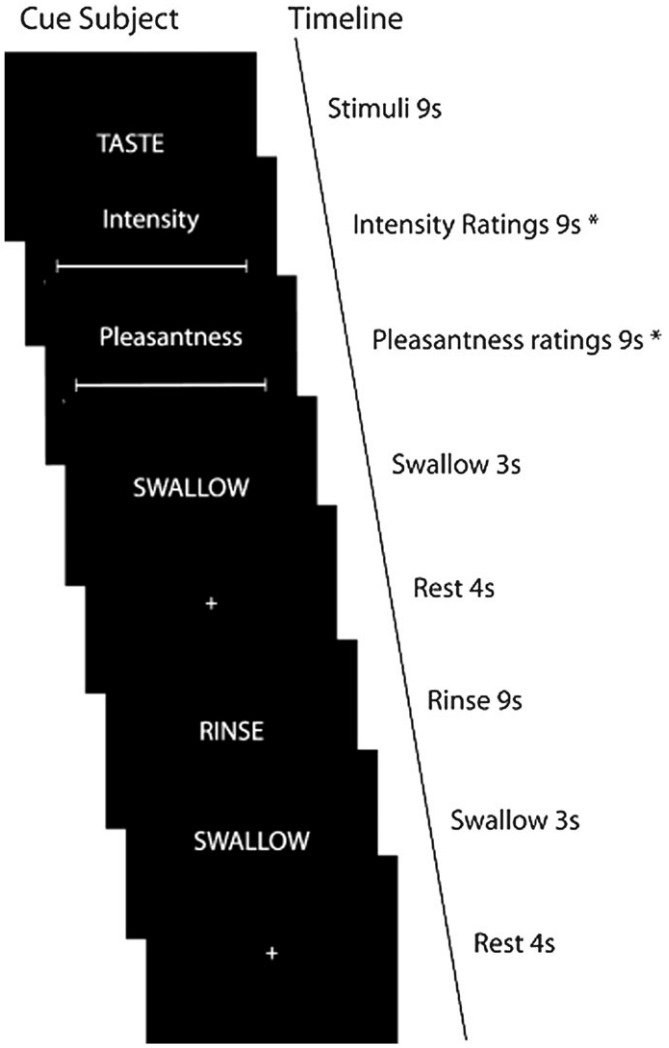

Figure 1 fMRI paradigm. Timeline of one cycle of tasting during an fMRI run. "*" Trials that included ratings took 50 s (4 of 7 trails), trails without ratings lasted for 32 s. Left in figure cues shown to the subject during the trail.

Stimuli

In a pilot study, 10 solutions of sucrose in water and 10 solutions of NaCl in water ranging from 0 to 1.25 M were rated by 30 normal-weight subjects (male, mean age 29.6 ± 2.7 years) on perceived intensity, pleasantness, sweetness, and saltiness on 10 cm VAS's, labeled ''not at all'' and ''extremely.'' Using the average intensity ratings from this pilot study, the concentrations for low, middle, and high intensity were determined such that low intensity corresponded with an average VAS score of 3, middle intensity corresponded with 5.5, and high intensity corresponded with 8.0 cm. The 4 concentrations chosen for both sucrose and NaCl were 0, 0.13, 0.50, and 1.0 M. These concentrations are referred to as ''zero,'' ''low,'' ''middle'', and ''high'' intensity.

Functional magnetic resonance imaging data acquisition

The scans were performed on a 3 T Philips Achieva MRI scanner at the University Medical Center Utrecht. A 2D single-shot echo-planar imaging sequence was used (time repetition/time echo [TR/TE] = 1600/23 ms, flip angle = 90°, field of view [FOV] = 256 × 208 mm, 30 interleaved axial slices, voxel size = 4 × 4 × 4 mm). The total duration of each functional run was 21 min, during which 799 scans were obtained. After the functional run, a T_1-weighted anatomical scan was made (TR/TE = 61/8.4 ms, flip angle = 30°, FOV = 288 × 175 mm, 175 axial slices, voxel size = 1 × 1 × 2 mm).

Data analyses

Functional magnetic resonance imaging (fMRI) data were preprocessed and analyzed using SPM5 (Wellcome Department of Imaging Neuroscience) run with MATLAB 7.5 (The Mathworks Inc.) and the WFU Pickatlas tool (Maldjian et al. 2003). First, the functional volumes of every subject were realigned to the first volume of the first run. Next, the anatomical image was coregistered with the mean functional image. Then the images were normalized (retaining 4 × 4 × 4 mm voxels) to Montreal Neurological Institute space (MNI space)(Evans et al. 1993) and spatially smoothed with a Gaussian kernel of 8 mm full-width at half-maximum. A statistical parametric map was generated for every subject by fitting a boxcar function to each time series, convolved with the canonical hemodynamic response function. Data were high-pass filtered with a cutoff of 128 s.

For every subject, 2 types of analyses were performed: 1) parametric modulation analyses and 2) analyses of taste activation. 1) For both sessions, 2 taste conditions were modeled with 2 parameters: an intensity parameter (first parameter) and pleasantness ratings (second parameter), once using the subjective intensity ratings (NaCl/sucrose intensity ratings) and once using the concentrations (NaCl/sucrose concentration; objective measure) as the intensity parameter. Because pleasantness and intensity are closely related (Veldhuizen et al. 2006), pleasantness needs to be taken into account when examining intensity effects. The responses to swallowing, rinsing, and rating were modeled but were not included in further analyses. The contrast images for linear parametric modulation of taste activation by subjective intensity ratings and by concentration were calculated for both sessions (sucrose and NaCl). 2) For both sessions, 8 conditions were modeled: tasting of zero, low, middle, and high concentration solutions, swallowing, rinsing, and giving VAS ratings. The responses to swallowing, rinsing, and rating were not included in further analyses.

In summary, these analyses yielded 2 modulation contrast images (for modulation by concentration and by subjective intensity) and 4 taste activation contrast images (zero, low, middle, and high intensity) per subject per session. The motion correction parameters from the realignment procedure were added to all models as regressors to regress out motion-related variance.

For the group analyses, the modulation contrast images of both sessions of all subjects were entered into a paired t-test. Two paired t-tests were done using the parametric modulation contrast images: one with the contrast images of modulation by intensity ratings and one with the contrast images of modulation by concentration. Lastly, the contrast images of taste activation were entered into a 2 × 4 analysis of variance (ANOVA) with taste (sweet and salt) and concentrations (0, 0.13, 0.50, and 1 M) as factors. Parameter estimates of taste activation by the different solutions were obtained from this ANOVA with the use of Marsbar (MARSeille Boite A Regions d'interet). Per subject 8 mean parameter estimates were calculated (one for every concentration in the 2 taste sessions). Parameter estimates were normalized per subject by using the parameter estimate of the zero concentration as a baseline measurement. A priori regions of interest (ROIs) were the insula, amygdala, striatum (putamen + caudate), pons, and cerebellum. These regions have been shown to respond to differences in taste (Small et al. 2003) and/or odor intensity (Anderson et al. 2003; Winston et al. 2005). ROI masks were made using the WFU Pickatlastool (Maldjian et al. 2003).

The subjective ratings obtained during the scans were analyzed as follows: Mean intensity ratings were calculated per condition (sucrose and NaCl) and per concentration (0, 0.13, 0.50, and 1.0 M). Subsequently, these average intensity ratings were compared between the sweet and the salty session with paired t-tests, for every concentration. The same was done for the mean pleasantness ratings. The correlation (r) between the subjective intensity ratings and the given concentration were also calculated. Statistical analyses of the subjective ratings were done with SPSS 16.0 (SPSS Inc.).

Results

Subjective ratings

Intensity and pleasantness ratings are shown in Figure 2. Mean intensity ratings did not differ between the sucrose and NaCl solutions for any concentration (paired t-tests $P > 0.05$). Higher concentrations of both tastes were rated as more intense. Mean ± standard deviation VAS ratings of NaCl intensities were 1.5 ± 0.9 (zero), 3.0 ± 1.5 (low), 6.2 ± 1.8 (middle), and 8.5 ± 0.9 cm (high). Mean sweet intensities ratings were at 1.7 ± 0.6 (zero), 2.6 ± 1.2 (low), 6.3 ± 1.4 (middle), and 8.0 ± 1.0 cm (high). Subjective intensity ratings were highly correlated with concentration for both tastes (sucrose, $r = 0.92$ $P < 0.01$ and NaCl, $r = 0.90$, $P < 0.01$) (Figure 3). Mean pleasantness ratings dropped with increasing concentration for both tastes as shown in Figure 2 right panel (Mean saltiness: 5.7 ± 1.6, 4.9 ± 1.0, 3.5 ± 1.2, and 1.9 ± 1.1 cm. Mean sweetness ratings were 5.1 ± 1.3, 5.1 ± 1.2, 5.0 ± 1.7 and 4.4 ± 1.9 cm). However, only the

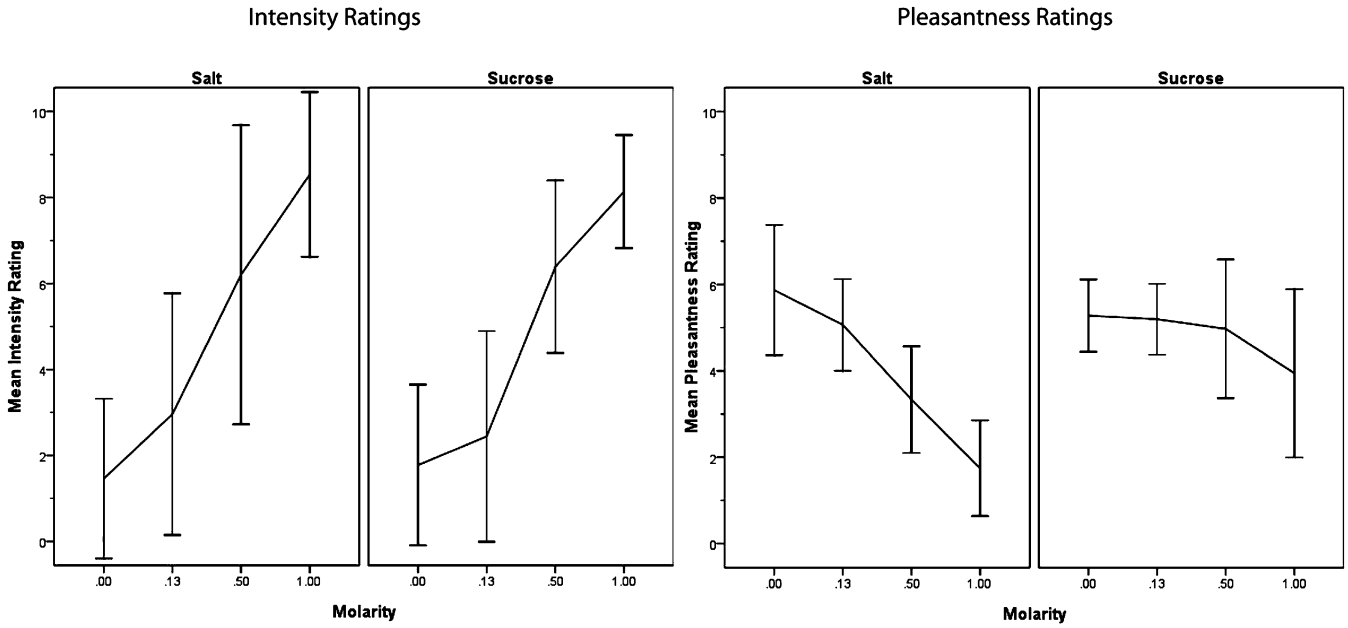

Figure 2 Mean (±standard deviation) VAS ratings of intensity (2 left graphs) and pleasantness (2 right graphs) of the 4 salt and sucrose solutions obtained during the fMRI task (N = 14). The mean intensity ratings per concentration did not differ between the 2 conditions (paired t-tests, $P > 0.05$). The mean pleasantness ratings per concentration only differ when tasting the highest concentration (paired t-tests, $P < 0.05$).

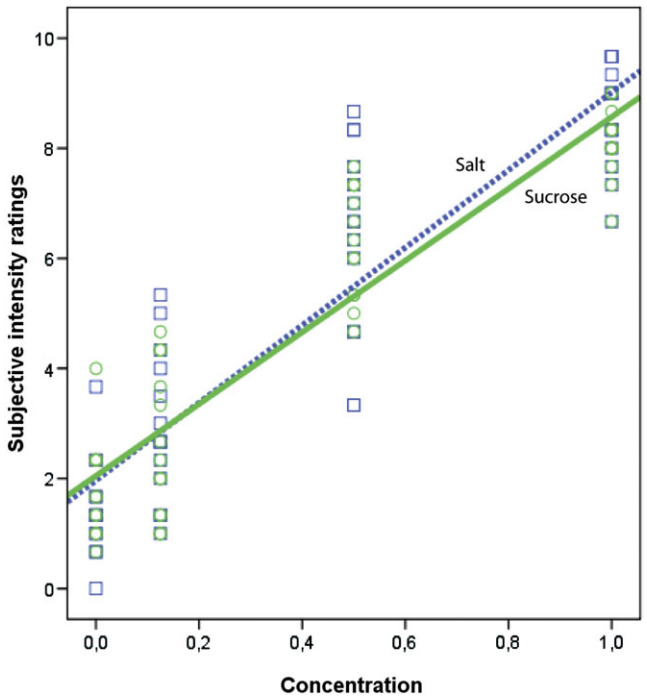

Figure 3 Correlation between VAS ratings of stimulus intensity and concentration of tastes solutions. The correlation for the sucrose is represented by the solid line (r = 0.915). NaCl correlation is represented by the dotted line (r = 0.896) (Pearson's correlation, $P < 0.01$).

pleasantness of the highest concentration of the NaCl solutions decreased significantly compared with the zero concentration (paired t-test, $P < 0.05$).

fMRI results

Intensity in the brain: NaCl and sucrose

When combining response to sweet and salty taste, taste activation in the middle insula was modulated by concentration, as well by intensity ratings (bilaterally). Taste activation in the right amygdala and right putamen covaried with concentration but not with perceived intensity. This is shown in Table 1.

NaCl

Brain regions whose response covaried with NaCl intensity ratings and NaCl concentration are shown in Table 2. In the NaCl condition, taste activation was modulated by intensity ratings in the middle insula (bilaterally), right amygdala, left hippocampus, right putamen, and in the caudate (bilaterally). Activation in the middle insula (bilaterally), right amygdala, and the right putamen was modulated by NaCl concentration. Positive modulation of taste activation in the middle insula by NaCl concentration and intensity ratings is shown in detail in Figure 4. Modulation of amygdala taste activation by NaCl concentration and intensity is shown in Figure 5.

Sucrose

Brain regions whose response covaried with sweet intensity ratings and sucrose concentration are shown in Table 3. Modulation of taste activation by sweet intensity ratings was found in the right middle insula (Figure 6). Modulation

Table 1 Brain regions where taste activation is modulated by intensity and concentration of taste[a]

Region	Cluster size[b]	Peakvoxel coordinates[c]			*Z* score
		x	*y*	*z*	
Intensity ratings					
Whole brain					
L middle insula	16	−40	−12	16	4.26
Concentration					
Whole brain					
R middle insula	232	32	12	−4	5.07
		48	12	−4	4.60
Insula ROI					
R middle insula	57	32	16	4	4.96
		48	12	−4	4.60
		40	8	−8	4.47
L middle insula	13	−36	−12	4	3.59
Striatum ROI					
R putamen	35	32	12	4	5.07
Amygdala ROI					
R amygdala	13	28	0	−12	3.62

[a]Taste intensity modulation was tested by performing a *t*-test on the contrast images of modulation of taste activation by intensity ratings and concentration for all brain voxels by using statistical parametric mapping. L, left: R, right; ROI.
[b]Reported clusters were thresholded at $P < 0.005$ (uncorrected for multiple comparisons) with a cluster extent of $K > 20$ voxels for whole brain and $K > 8$ voxels for ROIs.
[c]Voxel coordinates are in MNI space (Evans et al. 1993).

by sweetness intensity in the left insula was not statistically significant (MNI –42, –20, 20), Z score = 3.0 $P < 0.01$). Also, in the left thalamus modulation of taste activation by sweetness was found. Taste activation in the right middle insula and in the right putamen was positively modulated by sucrose concentration (Table 3). Taste activation in the amygdala was not modulated by sucrose concentration or perceived sweetness intensity.

NaCl versus sucrose

The differences between modulation of taste activation by NaCl and by sucrose are shown in Table 4 (NaCl > sucrose). Modulation of taste activation in the anterior insula was stronger from saltiness than from sweetness, that is, anterior insula activation increased more with NaCl concentration then with sucrose concentration. There were no brain areas that were modulated more strongly by sucrose concentration than by NaCl concentration.

Table 2 Brain regions where taste activation is modulated by the degree of saltiness[a]

Region	Cluster size[b]	Peakvoxel coordinates[c]			*Z* score
		x	*y*	*z*	
Intensity ratings					
Whole brain					
L insula	98	−40	−12	16	4.87
L hippocampus		−36	−28	−8	4.17
R insula	311	32	20	16	4.78
R inferior frontal gyrus		56	16	12	4.38
Insula ROI					
L insula	18	−40	−12	16	4.68
		16	20	−8	3.99
R insula	78	36	12	4	4.30
	17	40	−12	8	3.51
Striatum ROI					
R caudate	14	20	−20	24	5.00
L caudate	11	−16	−8	24	4.15
R putamen	24	24	8	0	3.39
Amygdala ROI					
R amygdala	11	32	4	−20	4.04
Concentration					
Whole brain					
R insula	149	32	16	0	4.05
R inferior frontal gyrus	42	44	36	8	3.82
L precentral gyrus	47	−36	−20	64	3.69
R inferior frontal gyrus		56	16	12	4.38
Insula ROI					
R insula	41	32	16	4	4.60
L insula	13	−40	−12	4	3.27
R insula	78	36	12	4	4.30
Striatum ROI					
R putamen	24	32	12	0	4.56
Amygdala ROI					
R amygdala	11	24	0	−12	3.60

[a]Saltiness modulation was tested by performing a *t*-test on the contrast images for modulation of taste activation by intensity ratings and concentration for all brain voxels by using statistical parametric mapping. L, left: R, right; ROI.
[b]Reported clusters were thresholded at $P < 0.005$ (uncorrected for multiple comparisons) with a cluster extent of $K > 20$ voxels for whole brain and $K > 8$ voxels for ROIs.
[c]Voxel coordinates are in MNI space (Evans et al. 1993).

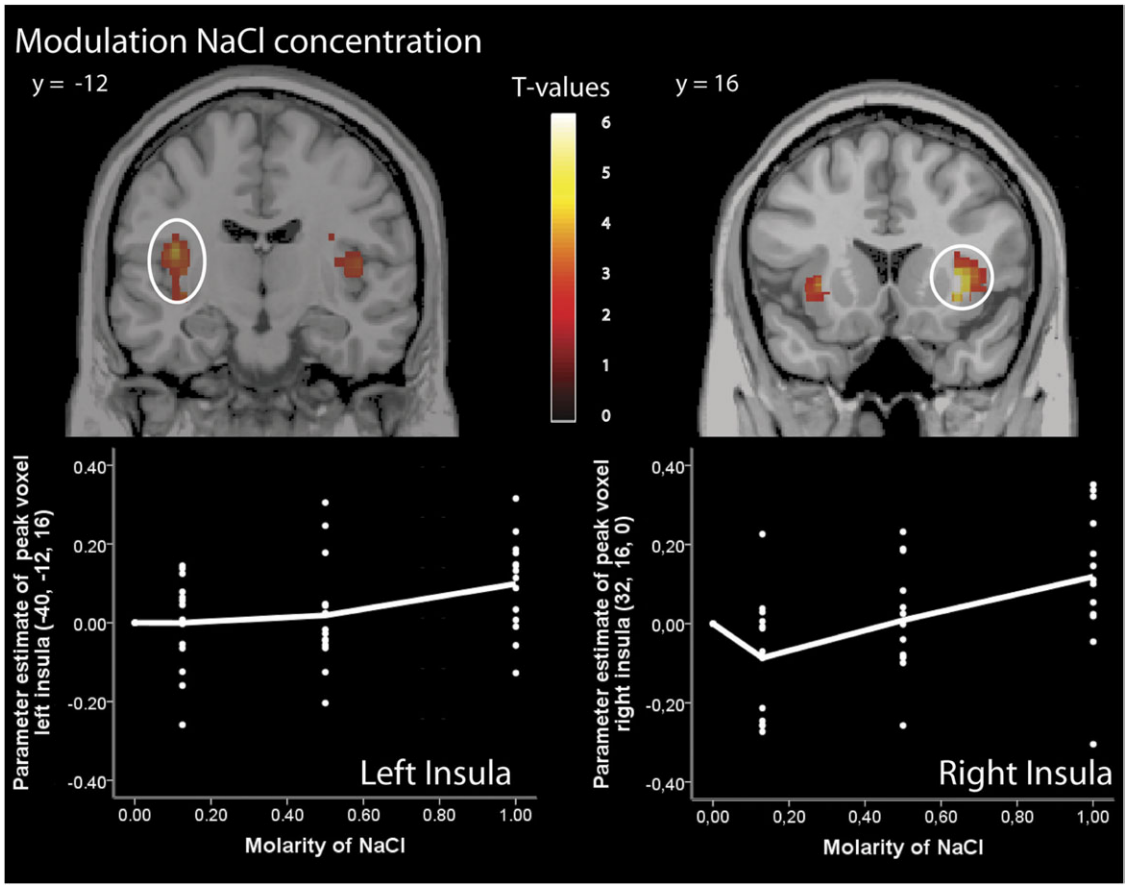

Figure 4 Modulation of insula taste activation by saltiness. Left: statistical parametric maps of the *t*-tests, thresholded at $t = 2.8$ ($P < 0.005$) and mean parameter estimates of taste activation for the left insula peak voxels per concentration. Right: statistical parametric maps of the *t*-tests, thresholded at $t = 2.8$ ($P < 0.005$) and mean parameter estimates of taste activation for the right insula peak voxels per concentration. Circles indicate the insula clusters.

Discussion

We determined the brain areas where taste activation covaries with stimulus intensity, using a range of NaCl and sucrose solutions. Perceived intensity and concentration were highly correlated and therefore modulation by these 2 factors yielded similar brain areas.

The first study examining the representation of taste intensity in the brain compared brain responses between 2 low intensity tastes and 2 high intensity tastes (sweet and bitter) (Small et al. 2003). This classical fMRI approach compares taste activation, that is, how robustly tasting induces a blood oxygen level–dependent (BOLD) response. In contrast, we used parametric modulation analyses in conjunction with a range of 4 concentrations of each stimulus type. Parametric modulation is a more recently developed approach (Buchel et al. 1996), which tests for a linear correlation between a parameter and the amplitude of the BOLD response. Using this approach, we examined several ROI's based on the study of Small et al. (2003) and found modulation of taste activation by intensity in the middle insula (bilaterally), amygdala, striatum, and hippocampus but not in the pons and cerebellum.

Insula

We found that middle insula taste activation was modulated by intensity differences bilaterally. This is in line with the findings of Small et al. (2003) that high intensity tastes activate the middle insula more strongly than low intensity tastes. Schoenfeld et al. (2004) found a high interindividual variability in the exact part of the insula activated by the 5 basic tastes but considerable overlap between the insular regions activated by the different tastes. However, they did not account for possible effects of differences in pleasantness and intensity. We found in additional analyses on the group level that patterns of taste activation show great overlap and do not differ significantly between sweet and salty solutions (this study) and between sweet and savory drinks (Spetter MS, Smeets PAM, unpublished data). Nevertheless, interindividual differences may have decreased the power of our group analyses in the insula.

We found that taste activation in the anterior insula increased more with NaCl concentration than with sucrose concentration. The anterior insula is the putative primary taste cortex (Pritchard et al. 1986) and is known to respond

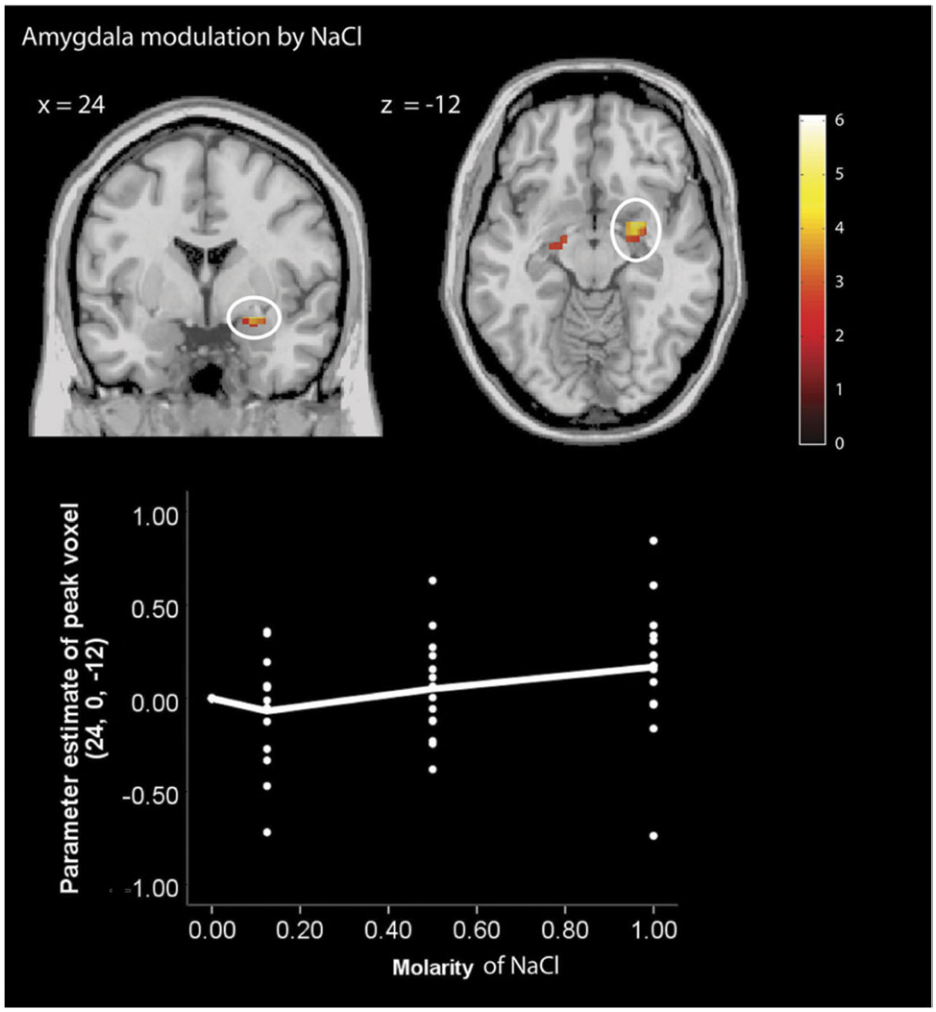

Figure 5 Modulation of amygdala taste activation by saltiness. Top: statistical parametric maps of the *t*-tests, thresholded at $t = 2.0$ ($P < 0.005$). Bottom: mean parameter estimates of taste activation for the amygdala peak voxels per concentration. Circles indicate the amygdala cluster.

to taste compared with a tasteless solution (Bender et al. 2009). However, it is also known to play a role in negative valence-specific responses in taste (Small et al. 2003). In our study, high saltiness was perceived as less pleasant than high sweetness. This suggests that the stronger modulation of anterior insula by taste activation by saltiness could be due to a valence difference.

Amygdala

Our results show that saltiness (both perceived intensity and concentration) modulates taste activation in the amygdala, whereas sweetness did not affect amygdala activation. The amygdala has been associated with emotional processing of positive as well as negative stimuli (O'Doherty et al. 2001; Zald 2003). For food stimuli, amygdala activation has been shown to be associated with reward (Baxter and Murray 2002) and with the intensity of odors (Anderson et al. 2003). Winston et al. (2005) found that amygdala odor activation was only affected by odor intensity when an odor was perceived as pleasant or unpleasant, that is, the amygdala did not respond to neutral odors. In our study, pleasantness ratings of the sucrose solutions remained approximately neutral, whereas the pleasantness of NaCl solutions decreased with increasing concentration. Thus our results suggest, in line with previous findings for odors (Winston et al. 2005), that the amygdala codes for intensity but only for nonneutral stimuli, that is, not independent of valence. According to Veldhuizen et al. (2006), the hedonic tone and subjective intensity of a stimulus are related and therefore difficult to separate. Previous brain imaging studies (Small et al. 2001, 2003; Anderson et al. 2003) and our study show there is a functional interplay between intensity and pleasantness.

Striatum

Both sweetness and saltiness modulated taste activation in the striatum (putamen and caudate). This is in line with the findings of Small et al. (2003) that striatal (putamen)

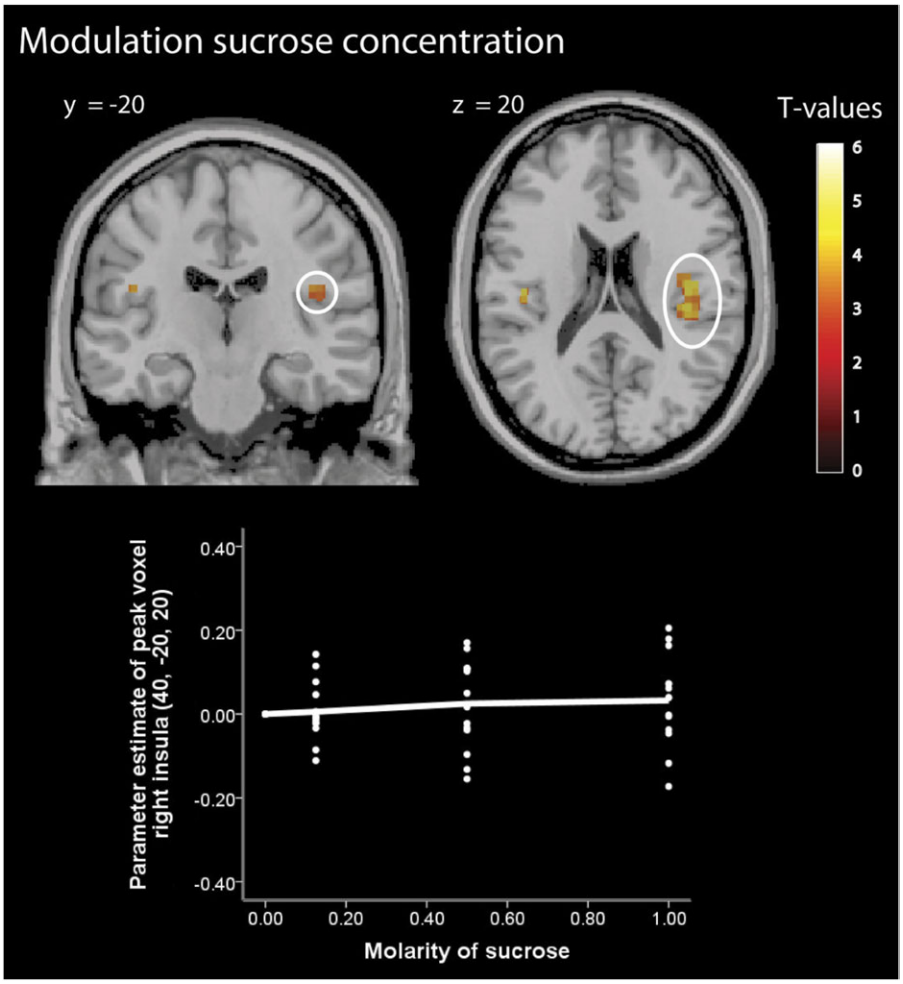

Figure 6 Modulation of insula taste activation by sweetness. Top: statistical parametric maps of the *t*-tests, thresholded at $t = 2.8$ ($P < 0.005$). Circles indicate the insula cluster. Bottom: mean parameter estimates of taste activation for the insula peak voxel per concentration.

activation is affected by intensity differences and may reflect (the assessment of) reward value and/or affective value. Rudenga et al. (2010) showed that when tasting a potentially nutritive stimulus (sucrose and NaCl), the connectivity between the insula and striatum was enhanced compared with potentially harmful tastes. The dorsal striatum encodes consummatory food reward, whereas the ventral striatum responds preferentially to food anticipation and is involved in forming predictions of affective value. For sweetness this is not surprising, given the rewarding nature of sucrose solution, but for saltiness, this is a novel finding (de Araujo et al. 2008).

Hippocampus

We found modulation of hippocampal taste activation by saltiness ipsilateral to the site of amygdala activation. This concurs with the findings of Zald et al. (1998) that tasting saline activates the hippocampus (contrasted with water) but has not been reported in other neuroimaging studies that administered basic taste stimuli (Small 2006). Zald et al. (1998) noted that hippocampus activation by saline primarily occurred among subjects who found the saline extremely aversive. This suggests that, similar to the amygdala, the modulation of taste activation in the hippocampus may be caused by aversive taste of salt rather than by intensity alone.

Sweetness versus saltiness

The process of tasting starts on the tongue. All areas of the tongue can respond to the 5 basic tastes (Chandrashekar et al. 2006). In rodents, the mean firing rate of taste cells is similar for sucrose and NaCl (Nishijo and Norgren 1990). Moreover, the mean responses to both NaCl and sucrose have been found to increase monotonically with concentration (Nishijo and Norgren 1990). Although the mean firing rate of taste cells is similar for sucrose and NaCl, stimulation by sucrose or NaCl subsequently results in different

Table 3 Brain regions where taste activation is modulated by the degree of sweetness[a]

Region	Cluster size[b]	Peakvoxel coordinates[c]			*Z* score
		x	*y*	*z*	
Intensity ratings					
Whole brain					
R precental gyrus	34	64	−4	12	4.05
Insula ROI					
R insula	15	40	−20	20	3.83
Striatum ROI					
R putamen	11	28	8	8	3.69
Concentration					
Whole brain					
L thalamus	146	−16	−20	12	4.41
R insula	20	40	−20	20	3.31

[a]Sweetness modulation was tested by performing a *t*-test on the contrast images of modulation of taste activation by intensity ratings and concentration for all brain voxels by using statistical parametric mapping. L, left: R, right; ROI.
[b]Reported clusters were thresholded at $P < 0.005$ (uncorrected for multiple comparisons) with a cluster extent of $K > 20$ voxels for whole brain and $K > 8$ voxels for ROIs.
[c]Voxel coordinates are in MNI space (Evans et al. 1993).

Table 4 Brain regions where taste activation is differentially modulated by sweetness and saltiness[a]

Region	Cluster size[b]	Peakvoxel coordinates[c]			*Z* score
		x	*y*	*z*	
Intensity ratings					
Whole brain					
R frontal middle	196	32	48	12	4.65
Insula ROI					
L anterior insula	38	−32	20	−8	4.47
		−40	20	−8	4.21
R anterior insula	35	36	16	4	4.22
		28	24	−12	3.77
Concentration					
Insula ROI					
R insula	12	44	−12	8	4.01

[a]Modulation was tested by performing a *t*-test on the contrast images of modulation of taste activation by intensity ratings and concentration for all brain voxels by using statistical parametric mapping. L, left: R, right; ROI.
[b]Reported clusters were thresholded at $P < 0.005$ (uncorrected for multiple comparisons) with a cluster extent of $K > 20$ voxels for whole brain and $K > 10$ voxels for ROIs.
[c]Voxel coordinates are in MNI space (Evans et al. 1993).

patterns of taste transduction (Lindemann 2001) and involves different neurons (Schiffman 2000). This difference in taste transduction could explain the differences in modulation of amygdala and anterior insula activation by sweetness and saltiness. However, little is known about the NaCl taste transduction pathway (Roper 2009). In addition, these differences in peripheral taste transduction and the differences in modulation by sucrose and NaCl could be explained by their different physiological function. Both NaCl and sucrose are essential nutrients (Roper 2009). NaCl plays an essential role in maintaining electrolyte balance, as well as in the regulation of blood pressure and blood volume and in water homeostasis (Garcia-Bailo et al. 2009). Because a high NaCl intake can disturb the electrolyte balance and other regulation processes, NaCl intake is strictly regulated. Sucrose intake, on the other hand, is not so strictly regulated. Sucrose is a source of energy for the body and carbohydrate (as well as other macronutrient) intake is mainly limited by availability and by satiety mechanisms (Schwartz et al. 2000). As a result, sucrose intake is tolerable for the body in far greater amounts. This may explain why neuronal activation in the amygdala and anterior insula was higher for NaCl than for sucrose solutions. The higher sensitivity of these brain areas to NaCl concentration may reflect the strict monitoring of NaCl intake.

Conclusions

In conclusion, our results suggest that taste intensity is represented in the middle insula. Despite similar subjective intensity ratings, modulation of taste activation in the anterior insula by NaCl increased more with concentration than that by sucrose. This greater responsiveness of the anterior insula to saline (compared with sucrose) intensity differences, as well as the modulation of amygdala activation by NaCl taste intensity and concentration can be explained by the fact that intensity and pleasantness are closely related (Veldhuizen et al. 2006), and valence is an important factor when perceived intensity changes. Given the potentially unpleasant and artificial nature of a pure NaCl and sucrose solutions, subsequent studies should use sweet and savory foods to corroborate and extend our finding. This may further elucidate potential differences in satiation for sweet and savory foods (Weenen et al. 2005).

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