Food Quality and Preference 68 (2018) 304–314

Contents lists available at ScienceDirect

Food Quality and Preference

journal homepage: www.elsevier.com/locate/foodqual

Aroma effects on food choice task behavior and brain responses to bakery food product cues

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ARTICLE INFO

Keywords:
Aroma
Food choice behavior
Functional magnetic resonance imaging
Reward
Bakery products

ABSTRACT

Bread, and especially whole grain bread is an important source of dietary fibers. It was tested with behavioral and fMRI measures whether bread becomes more attractive when it is presented with bread aroma.

Twenty-eight healthy normal-weight women were exposed to images of bakery products (brown bread, white bread and cookies) without aroma or with a congruent (bread aroma) or non-congruent ("warm wood") aroma.

In general, product effects were larger than aroma effects. Images of brown bread were preferred over images of white bread as shown by direct comparisons, choice reaction times, as well as liking and wanting scores. Aroma had no effect on liking and wanting, but did affect food choice task behavior, where images of brown bread were preferred more often in the presence of warm wood aroma and images of cookies were preferred more often in the presence of bread aroma. The fMRI data suggest that bread aroma may increase the salience of bakery products compared to no aroma and a non-food aroma. Specifically, bread aroma induced greater activation for cookies in areas related to reward anticipation. The correlations between behavioral measures and brain responses suggest lower attention for and a habitual response to brown bread and higher attention and a more goal-directed response to white bread.

In conclusion, aroma can affect choice task behavior for brown and white bread albeit in an incongruent manner. The more habitual response to brown compared with white bread suggested by the neural data underscores that nudging towards brown bread consumption with (bread) aroma will probably not be effective.

1. Introduction

Bread is a basic food product that is largely consumed all over the world. Bread is an important contributor to grain and fiber intake, which in general is too low.

A possible strategy to increase the bread consumption is to make bread more attractive, for example by using bread aroma. Supermarkets and bakeries have long been using bread aromas to facilitate sales of bread in general. The smell of freshly-baked bread is supposed to guide consumers towards the bread department and increase sales. Even though this kind of use of aromas has to the best of our knowledge not been scientifically tested, other effects of bread aroma such as improving mood have been demonstrated (Zhou, Ohata, & Arihara, 2016). More in general, food aromas have been shown to increase food appetite for congruent products, in terms of both taste and energy density, irrespective of hunger state (Zoon, de Graaf, & Boesveldt, 2016). Food aromas also affected food choice, where for example exposure to citrus aroma reduced selection of cheese (de Wijk & Zijlstra, 2012). Also, aromas have been found to affect behavior in restaurants (Guéguen & Petr, 2006), and shops (de Wijk, Maaskant, Kremer, Holthuysen, & Stijnen, 2017). The reported effects of aromas on food appetite, food choice and behavior in an eating environment motivated the hypothesis that bread aroma may increase bread liking and wanting, and affect choice behavior of bakery products.

Not all bread is equally healthy. Different studies have shown a protective effect of whole grain intake on prevention of several noncommunicable diseases (Aune, Norat, Romundstad, & Vatten, 2013; Jonnalagadda et al., 2011; Slavin, 2003; Wu et al., 2015), contributing to the recommendation to replace refined grains with whole grains (Aune et al., 2013). Despite these recommendations, whole grain intake is generally lower than recommended. Approximately 38% of Dutch bread sales is whole grain bread while about 15% of bread sales

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https://doi.org/10.1016/j.foodqual.2018.03.015
Received 12 October 2017; Received in revised form 16 February 2018; Accepted 26 March 2018
Available online 09 April 2018
0950-3293/

concerns white flour bread (de Wijk et al., 2016). A shift from the consumption of bread made from refined white flour to 100% whole grain flour bread would be ideal from a health recommendation perspective. However, changing intake of refined bread to brown bread, which contains a mixture of refined white and whole grain flour, would already increase whole grain intake. Thus, increasing the consumption of brown or whole grain bread can contribute to the increase of whole grain and fiber intake, and thereby to a healthier diet. Thus, a second hypothesis for this study is that bread aroma may differentially affect liking, wanting and choice of refined and whole grain (brown) bread.

Functional MRI (fMRI) can be used to gain insight in the brain processes underlying food evaluation and food (Smeets, Charbonnier, van Meer, van der Laan, & Spetter, 2012). The most common fMRI approach is to measure brain reactivity towards food cues, such as visual, odor, and gustatory cues. Such food cues are commonly considered a proxy for exposure to real food-related sensory signals such as seeing foods, however, food aroma's and food images are also present in the environment. Several studies have shown relationships between neural food cue reactivity and food preference and food choice behavior. For example, in a study using visual cues of food products differing in hedonic value, it was shown that foods of high hedonic value elicited greater activation of brain reward regions than neutrally rated foods (Cornier, Von Kaenel, Bessesen, & Tregellas, 2007). Similarly, Griffioen-Roose and colleagues have shown that after protein depletion the brain response to savory combined visual and olfactory food cues was greater in areas related to reward and preference (Griffioen-Roose et al., 2014). These and other studies show that the hedonic value and salience of foods can affect brain responses in reward-related areas (van der Laan, de Ridder, Viergever, & Smeets, 2011). In line with this, food cue reactivity has been shown to predict subsequent food choice. In an fMRI study with visual cues, Mehta and colleagues found relations between activation of reward-related brain areas such as the striatum and orbitofrontal cortex by visual cues of high- and low calorie foods, and subsequent food choice and food intake (Mehta et al., 2012). Lawrence et al. have shown that visual food cue related activity in the nucleus accumbens, a key brain region for food motivation and reward, was associated with subsequent snack food consumption, but not with self-reported hunger, or explicit wanting and liking for the snack. In contrast, food cue reactivity in the ventromedial prefrontal cortex was associated with subjective hunger/appetite, but not with consumption (Lawrence, Hinton, Parkinson, & Lawrence, 2012). These studies illustrate that differences in neural food cue reactivity can be linked with subsequent food choice.

The present study aimed to assess the effects of bread aroma on liking of, choice task behavior and brain responses to bakery food products using a combination of behavioral measures and neuroimaging (fMRI). More specifically, this combined approach aimed to elucidate the role of bread aroma in food choice, liking and wanting for brown bread, white bread and cookies. Briefly, the study combined two approaches in the presence of a bread aroma, a non-food aroma (wood) and in the absence of aroma. Firstly, food choice behavior was examined with the use of images of bakery products, i.e. brown bread (whole grain meal or whole grain meal mixed with refined white flour), white refined bread and cookies. In addition, brain activation in response to viewing these bakery products in the presence and absence of the same aromas was measured. It was hypothesized that bread aroma would increase liking, wanting and choice for bread and that this would be paralleled in increased activation of reward anticipation-related brain areas such as the striatum and orbitofrontal cortex.

2. Materials and methods

2.1. Participants

This study was conducted in accordance with the Declaration of Helsinki and approved by the Medical Ethical Committee of Wageningen University & Research (NL53942.081.15). All participants signed an informed consent form before participation. Participants were 28 healthy, normal-weight, right-handed women (age 22.0 ± 2.9 years, range: 18–31 years, body mass index (BMI) 21.99 ± 1.74 kg/m^2, range 18.96–24.84 kg/m^2, mean ± SD). They were recruited from the participant pool of Wageningen University & Research. Exclusion criteria included a BMI < 18.5 or > 25; being under 18 or over 35 y of age on the study day; smoking; drinking on average > 14 units of alcohol per week; lack of appetite, having an energy restricted diet during the last two months; a change in body weight > 5 kg in the past two months; having difficulties with swallowing/eating; having a taste or smell disorder; stomach or bowel diseases, diabetes, thyroid disease or any other endocrine disorder; diabetes, use of daily medication other than oral contraceptives, aspirin and paracetamol, eating bread less than 4 times a week, disliking cookies, and being pregnant or lactating. In addition, there were MRI exclusion criteria such as claustrophobia and having metal implants or metal objects on the body that cannot be removed. Participants were informed that the study measured brain responses towards images of bread and cookies in the presence or absence of aroma with the overall aim to gain insight in the drivers of eating behavior.

2.2. Experimental procedures

Participants participated in three sessions in chronological order: a training session, an fMRI session, and a food choice session. The training and food choice sessions were conducted in the Wageningen University & Research facilities of the Restaurant of the Future (Wageningen, The Netherlands). The fMRI session was conducted at the Gelderse Vallei Hospital (Ede, The Netherlands). The time between the fMRI session and the food choice session was 2–3 weeks.

2.2.1. Training session

During the training session BMI was measured, part of the experimental fMRI procedure was practiced in a dummy MRI scanner, aroma identification was tested, and several questionnaires were administered.

2.2.2. MRI practice session

During the fMRI training session participants were placed in a dummy MRI scanner to get familiarized with the fMRI procedures. They were presented with three blocks of five food-related images either combined with a low concentration bread aroma (block 1), no aroma (block 2) or a high concentration bread aroma (block 3). The aroma was a bread flavor (Bread flavor liquid sc513519, International Flavors & Fragrances I.F.F. (Nederland) B.V, Hilversum, the Netherlands) diluted with propylene glycol to 0.05% v/v and 1% v/v for the low and high concentration respectively. Aromas were presented using a Lundström olfactometer (Lundström, Gordon, Alden, Boesveldt, & Albrecht, 2010) and delivered through a nose piece in each nostril (3 L/min). Participants were instructed to look at the images and to remember for each of the three blocks whether an aroma was present, the type of aroma, the intensity, and how pleasant it was. The total time it took to place the participant in the dummy MRI scanner, perform the task and take the participant out of the scanner was 15–20 min. After the dummy scan session, participants filled in a questionnaire regarding the presence, nature, intensity, and pleasantness of the aromas.

2.2.2.1. Aroma identification test. Aroma identification was tested using the odor identification part of the 16-item Sniffin' Sticks test (Hummel, Sekinger, Wolf, Pauli, & Kobal, 1997) (mean score 13.39 ± 1.40). Participants had to correctly identify 11 of the 16 aromas. One participant identified only 10 aromas correctly, but since she was able to smell and identify the aromas used in the study it was decided to include her as well.

Table 1
Mean scores of the participants on the HTAS questionnaire. Theoretical score ranges from 1 to 7.

HTAS Questionnaire	Mean score	SD	Minimum score	Maximum score
General Health Interest	3.70	0.50	2.88	5.38
Natural Product Interest	3.94	0.63	2.33	5.17
Light Product Interest	3.93	0.43	2.50	4.67
Pleasure	4.31	0.62	2.83	5.33
Using Food as a Reward	4.10	0.68	2.33	5.00
Craving for Sweet Foods	3.48	0.52	2.67	4.83

2.2.2.2. Questionnaires. Participants filled out five questionnaires to measure impulsiveness, avoidance/inhibition, eating behavior, health and taste attitudes, discounting/impulsivity, and food preferences. Only HTAS and food preference results are reported here. The participants scored average on health interest and craving for sweet foods, and a little above average on natural and product interest, pleasure and using food as a reward (Table 1).

2.2.3. Behavioral session

The behavioral session consisted of a modified version of the Leeds Food Preference Questionnaire (LFPQ) (Finlayson, King, & Blundell, 2007, 2008) in which participants first performed a forced-choice task and then rated wanting and liking of bakery product images. Participants were placed in front of a monitor and instructed that they would be shown pairs of food images of brown bread, white bread and cookies (food choice task) from which they had to select the food that they would prefer to eat. Choice response times were also recorded. Next, single food images were rated on a 100-unit scale with regard to wanting ("How much would you want to each something of this food?") and liking ("How much would you like this now?"). After a brief practice run, the first of three blocks of food images started, each with 48 intended food choice questions in which images of each food type were paired equally often with images of the other types, 12 wanting and 12 liking questions for each of the three food types presented four times. Blocks were separated by a 5 min rest interval. Each block was presented either with wood aroma (Wood nr 821, AllSens, Oosterhout, the Netherlands, 1.1% v/v, 1000 ml/min, 1 s on 2 s off), bread aroma (Bread Flavor Liquid SC513519 IFF, Hilversum, the Netherlands, 0.25% v/v, 1000 ml/min, 1 s on 2 s off) or without aroma. There were no instructions to sniff or pay attention to the aromas. Aroma conditions were randomized across participants. E-Prime 2.0 software (Psychology Software Tools Inc., Sharpsburg, USA) was used for presentation of the food images and response acquisition. Aromas were presented with the same olfactometer as used in the MRI practice session.

After the session participants reported the time of their last meal and answered questions regarding the identity of the two aromas.

2.2.4. fMRI session

2.2.4.1. MRI data acquisition. A scan session consisted of three functional runs of ~15 min during which data was acquired using a T_2^*-weighted gradient echoplanar imaging sequence (TR = 2240 ms, TE = 25 ms, 90° flip angle, FOV = 192 × 192 mm, 43 axial slices, descending order, voxel size 3 × 3 × 3 mm) on a 3T Siemens Magnetom Verio (Siemens, Erlangen, Germany). The stack was tilted at an oblique angle of 30° to the anterior-posterior commissure line to reduce signal dropout in orbitofrontal cortex and ventral temporal lobe (Deichmann, Gottfried, Hutton, & Turner, 2003). In between two functional runs a high-resolution T_1-weighted anatomical scan was acquired (MPRAGE, TR = 1900 ms, TE = 2.26 ms, 9° flip angle, FOV = 256 × 256 mm, 192 sagittal slices, voxel size = 0.5 × 0.5 × 1.0 mm).

2.2.4.2. Stimuli and fMRI cue exposure task. The event-related fMRI task consisted of three runs of ~15 min. In each run, 120 image stimuli were presented in 5 blocks of 24 images. Blocks differed in aroma condition. Aromas were presented intranasally (inner diameter of the Teflon™ tubing 4 mm) using a Burghart OM6b olfactometer (Burghart, Wedel, Germany). To avoid mechanical stimulation the odor pulses were embedded in a constant flow of odorless, humidified air. There were three aroma conditions: no aroma, bread aroma (2% v/v, 1000 ml/min, 1 s on 2 s off (Bread Flavor Liquid SC513519 IFF, Hilversum, the Netherlands)) or wood aroma (2.2% v/v, 1000 ml/min, 1 s on 2 s off (Wood nr 821, AllSens, Oosterhout, the Netherlands)). Image stimuli consisted of images of either bread (brown bread (BB) or white bread (WB)) or cookies (CK). In each block eight images of each type were presented. The background was standardized (grey) and the amount of bread or cookies was kept constant for all images, i.e., the number of non-background pixels was the same for every image. Examples are given in Fig. 1. There were 26 brown bread, 12 white bread and 20 cookie images, but these numbers were doubled by making two variants for each image (showing a whole or a half bread, or showing a left-right mirrored image). Images were distributed in a semi-random order over the blocks, taking care not to repeat an image before all other options for that category had been presented. Note that the number of white bread images was lowest because there is a smaller variety of white breads available.

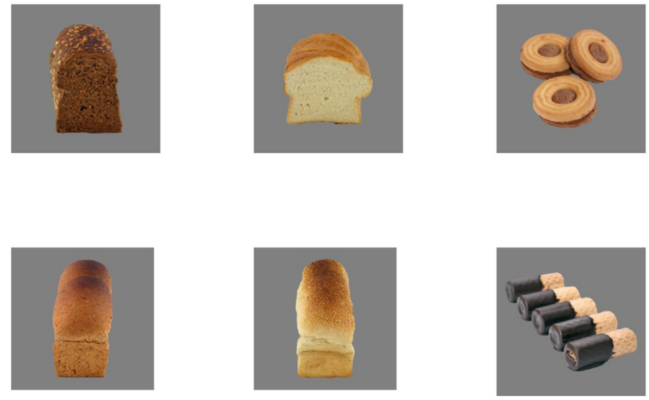

Fig. 1. Examples of pictures of brown bread (BB, left), white bread (WB, middle) and cookies (CK, right).

Aroma blocks started with a 6050-ms run in during which the aroma for that block was presented. Subsequently, aroma pulses were given during each image presentation, but not during the inter-stimulus interval. This prevents habituation, which would occur with continuous aroma flow. Aroma blocks ended with 8960 ms of washout. In all blocks, images were presented for 1240 ms, followed by an inter-trial interval varying between 2240 and 8960 ms, during which a white crosshair was shown on a grey background (Fig. 2). Before each image and/or aroma presentation the crosshair would turn red for 1000 ms, to cue the participants. Intertrial intervals were generated and the order of the different image types was optimized with the use of the Optseq2 algorithm (https://surfer.nmr.mgh.harvard.edu/optseq/) which provides temporal jitter to increase signal discriminability (Dale, 1999).

Before the start of the first run, the degree of hunger, thirst and comfort were rated on visual analogue scales using a button box (scale 0–100 units). Also, for each aroma liking and intensity ratings were collected four times, distributed over the three runs. Rating trials lasted 6720 ms. The questions asked were "How pleasant was the aroma?" and "How strong was the aroma?" with anchors "not at all" to "very much".

2.3. Data processing and analysis

2.3.1. Behavioral data (modified LFPQ)

Choice frequencies in the food choice task were tabulated per food pair and aroma condition. Chi square tests were performed to test for systematic effects of aroma.

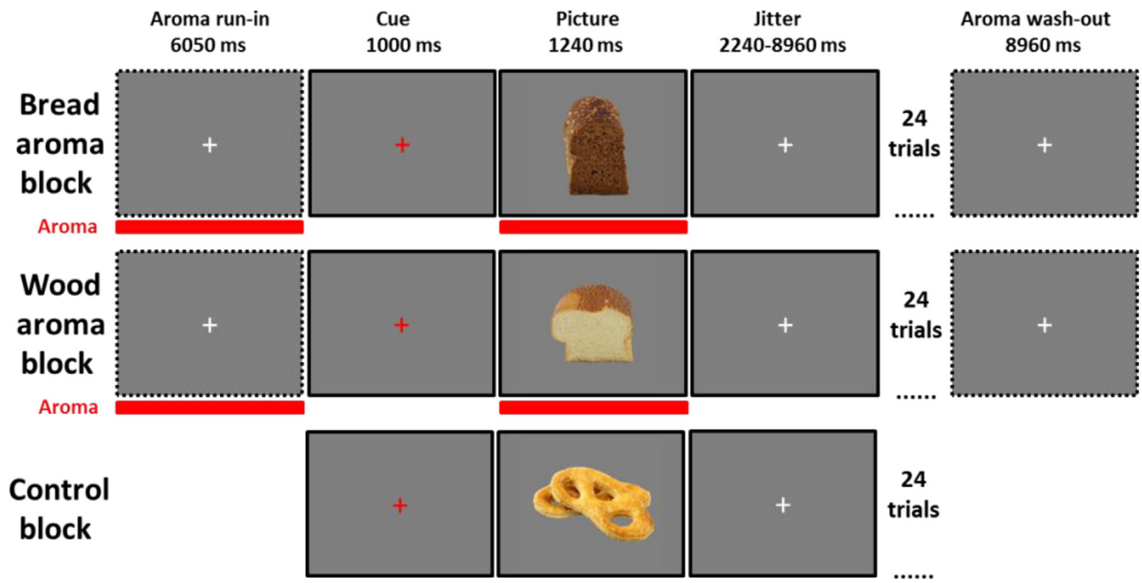

Fig. 2. Overview of the fMRI paradigm which consisted of 5 blocks of 24 picture presentations for the three aroma conditions. The order of these 15 blocks was randomized over 3 functional runs.

Choice reaction times were pre-treated following guidelines for analyses of implicit association tests (Greenwald, McGhee, & Schwartz, 1998). Reaction times shorter than 300 ms were replaced by 300 ms, and reaction times longer than 3000 ms were replaced by 3000 ms. Reaction times and wanting/liking ratings were analyzed with mixed model ANOVA with aroma condition (3: bread, wood, no aroma) and food type (3: brown bread, white bread, cookies) as fixed factors and participants as random factor. Behavioral data as well as subjective ratings in the fMRI session were analyzed with IBM SPSS Statistics 23.

2.3.2. fMRI data

fMRI data were pre-processed and analyzed with the SPM12 software http://www.fil.ion.ucl.ac.uk/spm) run with MATLAB 7.12 (The Mathworks Inc., Natick, MA). After slice time correction using the middle slice as a reference, functional images were realigned to the mean of the time series. The anatomical scan was co-registered to the mean of the realigned functional scans. A study-specific anatomical template was created using Diffeomorphic Anatomical Registration using Exponentiated Lie algebra (DARTEL, (Ashburner, 2007)) which estimates a best set of smooth deformations from every participant's tissues to their common average, applies these deformations to create a new average and then reiterates this process until convergence. The template was warped to MNI (Montreal Neurological Institute) space using an affine-only registration, and each participant's functional scans were warped using its corresponding smooth, reversible deformation parameters to the custom template space, and then to MNI space. The data were smoothed with a 6-mm full width at half maximum isotropic Gaussian kernel. After this the Volume Artefact tool from ArtRepair (Mazaika, Hoeft, Glover, & Reiss, 2009; Mazaika, Whitfield-Gabrielia, Reiss, & Gloverb, 2007) was used to detect and repair anomalously noisy volumes. Volumes that had over 1.0 mm scan-to-scan movement and scans with more than 1.5% deviation from the average global signal, were replaced by using linear interpolation of the values of neighboring scans.

Subject level analyses: 10 conditions were modelled, i.e., responses to each combination of image type (brown bread, white bread, cookies) and aroma condition (no aroma, bread, wood) and 'other' conditions (cue, aroma run-in, washout, rating). The responses to the latter conditions of no interest were modelled but not the focus of further analyses. A statistical parametric map was generated for every participant by fitting a boxcar function to each time series, convolved with the canonical hemodynamic response function. Data were high-pass filtered with a cut off of 128 s. To regress out motion-related variance, the motion-correction parameters from the realignment procedure were added to the model as regressors.

For every participant, parameters were estimated for all relevant comparisons (referred to as contrasts), yielding among others contrast images for each of the nine conditions versus baseline (three aroma conditions × three picture types) and for all aroma conditions minus the no aroma control condition (bread and warm wood minus no aroma for the three image types; six contrast images). First, the nine contrast images for each participant were entered into a flexible factorial model in SPM12 to assess main effects and interactions for the three aroma conditions and three bakery products. Second, the six contrast images with no aroma subtracted were entered into a similar flexible factorial model to assess main effects and interactions for the two aroma's and the three bakery products. Both flexible factorial models included Subject as the first factor. Third, to assess directional effects while controlling for aroma liking and intensity and to assess correlations between behavioral measures (food choice task outcomes) and brain activation selected contrast images were entered into one-sample *t*-tests with the relevant (difference in) mean liking and intensity ratings obtained during the scan session added as covariates. For visualization and for posthoc testing for the flexible factorial models average parameter estimates were extracted from significant clusters with the use of the MarsBar toolbox (http://marsbar.sourceforge.net/). Posthoc tests were done in SPSS using Bonferroni correction for multiple testing. To correct for multiple testing across brain voxels cluster extent thresholds for the minimum cluster size needed for a family-wise error-corrected $p = 0.05$ across the whole brain were determined for each analysis at $p = 0.001$ with the SPM cluster size threshold tool available at https://github.com/CyclotronResearchCentre/SPM_ClusterSizeThreshold. In addition, we report results at a threshold of $p = 0.001$, $k > 19$ contiguous voxels to allow for meta-analysis. Such a threshold inflates the risk of false positives, but it is more stringent than the arbitrary $k = 10$ threshold used by many studies (Eklund, Nichols, & Knutsson, 2016) and much more stringent than recommended by Lieberman and Cunningham (2009).

2.3.2.1. Reward ROI analyses. To specifically assess differences in reward anticipation-related brain activation by the different types of stimuli region of interest (ROI) analyses were performed on a set of

Table 2
Mean ± SE percentages of preferences based on images of brown bread over white bread, brown bread over cookies, and of white bread over cookies without aroma and in the presence of bread or warm wood aroma. Fifty percent would indicate no preference.

Product	No aroma control	Bread aroma	Warm wood aroma
Brown over white bread	72.1 ± 6.8	72.5 ± 6.3	75.7 ± 6.4
Brown bread over cookies	52.0 ± 6.1	46.4 ± 6.4	55.8 ± 6.5
White bread over cookies	72.1 ± 6.8	72.5 ± 6.3	75.7 ± 6.4

predefined regions that are known for their involvement in reward processing, including the bilateral striatum (caudate, putamen, pallidum), insula, supplementary motor area (SMA), and orbitofrontal cortex (OFC; orbital parts of the inferior, middle and superior frontal gyri) (Hoogendam, Kahn, Hillegers, van Buuren, & Vink, 2013; Knutson, Fong, Adams, Varner, & Hommer, 2001b; Knutson, Westdorp, Kaiser, & Hommer, 2000). Regions were based on definitions of the automated anatomical labeling-atlas (Tzourio-Mazoyer et al., 2002) and created using the WFU PickAtlas Toolbox implemented in SPM (Maldjian, Laurienti, Kraft, & Burdette, 2003). For ROI analyses an initial threshold of $p = 0.001$ was used with a subsequent FWE-corrected peak threshold of $p < 0.05$ corrected for the mask volume.

3. Results

3.1. Behavioral results: Food choice, liking and wanting

3.1.1. Food choice task

In a paired comparison, images of brown bread and cookies were preferred significantly over white bread images ($p < 0.05$, see Table 2). There was no effect of aroma on preference of images of brown and cookies over white bread. The type of aroma present (bread or wood aroma) significantly affected choice of brown bread images over images of cookies (ChiSquare = 3.9, $p < 0.05$; Table 2). Brown bread images were selected less often in the presence of bread aroma and more often in the presence of wood aroma.

Choice response times varied significantly between selected bakery product images (Product $F(2,193) = 6.0$, $p = 0.003$) (Fig. 3). Pairwise comparisons indicated that choice reaction times for brown bread images were significantly shorter than those for images of cookies ($p = 0.02$) and white bread ($p = 0.001$). Response times for images of cookies and white bread were not significantly different. Aroma condition did not affect choice response times (no significant main or interaction effect).

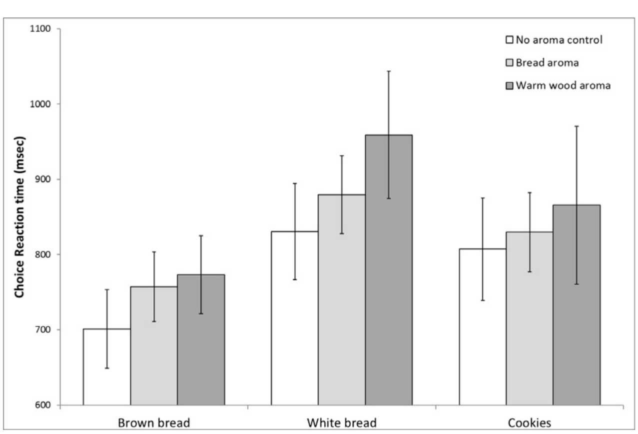

Fig. 3. Reaction time for food choices made in the different aroma conditions (mean ± SE).

3.1.2. Liking and wanting

Overall, wanting and liking ratings were not significantly affected by either food type or aroma condition (wanting: $F(1.8,49) = 2.3$, $p = 0.13$, liking $F(1.8,49) = 2.8$, $p = 0.07$; Table 3). Within-subject contrasts did show significant differences between images of brown and white bread for wanting ($F(1,27) = 5.8$, $p = 0.02$) and liking ($F(1,27) = 5.7$, $p = 0.02$).

3.2. fMRI results

3.2.1. Subjective ratings

In-scanner ratings were as follows (mean ± SE): comfortable 71 ± 3.2, hunger 64 ± 3.2, thirst 54 ± 3.2. Aroma ratings in Table 4 show that liking and intensity of bread aroma was higher than that of warm wood aroma.

3.2.2. Effects of aroma and bakery product type on cue reactivity

3.2.2.1. Aroma versus baseline. First, brain responses were assessed for all conditions versus baseline (flexible factorial model with 3 aroma conditions and 3 image types. This analysis parallels that of the behavioral data. Whole-brain results can be found in Supplementary Table 1. We here focus on the effects found in the reward ROIs because of possible a-specific effects due to the use of contrasts against baseline (Table 5).

There were significant main effects of aroma condition in the anterior cingulate and superior frontal gyrus (dorsomedial PFC): In the bilateral dorsomedial PFC and right anterior cingulate both aroma conditions elicited significant deactivations compared to control (all $p < 0.001$, Fig. 4). A trend for a main effect of aroma condition was found in the right amygdala (MNI(21, 3, −18), $p_{fwe} = 0.07$, $F = 19.3$): Only bread aroma tended to activate the right amygdala (posthoc comparisons with control and wood aroma, $p < 0.001$).

There were no main effects of image type in reward-related areas. There was an interaction between aroma condition and bakery product type in the anterior cingulate (Fig. 4): In the bread aroma condition, the response to cookie images was significantly greater than that to brown bread ($p < 0.05$). In addition, the response to brown bread during bread aroma was smaller than that during control aroma ($p < 0.05$). In addition, there was a trend for interaction effects in the dorsal putamen (MNI(18, 12, 9), peak $p_{fwe} = 0.07$, $F = 19.0$) and in the right Heschl's gyrus (MNI(42, −18, 12), $p_{fwe} = 0.10$, cluster-level $p_{fwe} = 0.07$, $F = 18.3$).

3.2.2.2. Aroma versus no aroma

3.2.2.2.1. To assess the overall effect of aroma. We contrasted the averaged aroma conditions with the no aroma condition in a one-sample *t*-test, while controlling for aroma intensity and liking (Supplementary Table 2). This test showed that the presence of aroma did not induce significantly greater activation during food image presentation (compared to no aroma) in any regions. Rather, there was greater activation in the bilateral medial PFC, including the anterior cingulate, right lateral OFC and left precentral gyrus during the no aroma control condition compared to the average aroma conditions. In this model, average aroma liking ratings correlated negatively with the difference in activation between aroma and no-aroma exposure in the dorsolateral PFC (middle frontal gyrus MNI(42, 45, 30), $Z = 4.2$, $k = 28$) and dorsal thalamus (MNI(−15, −18, 21), $z = 4.1$, $k = 34$).

3.2.2.2.2. Aroma versus no aroma. Next, we assessed specific effects for the two aromas by subtracting the no aroma control condition (flexible factorial model with the 2 aroma conditions minus control and 3 image types, Table 6; whole brain results in Supplementary Table 3). Again, we here focus on the effects found in the reward ROIs: There was a significant main effect of aroma in the right dorsal putamen and supplementary motor area. Bread aroma was associated with greater

Table 3
Mean ± SE wanting and liking ratings of brown bread, white bread and cookies in the three aroma conditions.

Product	Wanting			Liking		
	No aroma control	Bread aroma	Warm wood aroma	No aroma control	Bread aroma	Warm wood aroma
Brown bread	57.8 ± 3.6	55.6 ± 4.3	59.1 ± 3.9	58.7 ± 3.8	56.8 ± 4.0	57.9 ± 3.8
White bread	49.6 ± 4.0	47.4 ± 4.4	48.3 ± 4.2	49.9 ± 4.0	49.2 ± 4.4	48.0 ± 4.2
Cookies	57.7 ± 4.5	57.1 ± 4.6	55.7 ± 5.1	59.2 ± 4.8	60.7 ± 4.5	57.6 ± 4.8

Table 4
In scanner aroma ratings (n = 28, mean ± SE).

Rating	Bread	Warm wood	Delta Bread-Warm wood	p-value comparison[1]
Liking	60 ± 4.3	39 ± 2.6	21 ± 5.3	< 0.001
Intensity	69 ± 2.3	58 ± 1.9	11 ± 2.6	< 0.001

[1] Paired-samples *t*-test.

Table 5
Results of the reward ROI factorial analysis with 3 aroma conditions and 3 picture types (n = 28).[1]

Reward ROI region	Peak voxel coordinate (MNI)			Peak p_{fwe}	*F*-score
	X	*Y*	*Z*		
Main effect aroma condition					
L Anterior cingulate	-12	36	24	0.003	26.4
R Superior frontal gyrus/ dorsomedial PFC	9	48	24	0.03[2]	21.3
R Anterior cingulate	9	45	15		16.9
Main effect picture type					
	–	–	–	–	–
Interaction aroma x picture					
L Anterior cingulate	-3	3	27	0.01	23.5

[1] Flexible factorial model. Shown are clusters in reward ROIs with a small-volume corrected peak $p_{fwe} < 0.05$. See Fig. 5 for the direction of the effects.
[2] Cluster-level $p_{fwe} = 0.04$. L = left, R = right hemisphere. PFC = prefrontal cortex.

activation than wood aroma in both these regions ($p < 0.001$, Fig. 5).

There was no significant main effect of image type. However, there was an interaction between aroma type and image type in the supplementary motor area (SMA) and a trend for an interaction effect in the left anterior cingulate (MNI(−3, 3, 27), $p_{fwe} = 0.08$, F = 19.3): In the SMA, bread aroma was associated with greater activation for cookie images, while wood aroma induced deactivation for white-bread and cookie images. However, none of the post hoc comparisons reached significance. In the anterior cingulate, cookie images induced greater activation than brown bread in the presence of bread aroma (posthoc $p < 0.05$).

3.2.3. Bread versus wood aroma

3.2.3.1. To test for specific effects of the aromas. The responses to bread versus warm wood aroma across all product types were compared, controlling for differences in aroma liking and intensity. Note that this yields pure aroma effects since all common image differences are subtracted out. There was significantly greater activation during food image exposure in the left precentral gyrus and left dorsolateral PFC for bread compared to wood aroma (Supplementary Table 4).

3.2.3.2. Differential aroma effects on the response to bread images. The effects of bread and warm wood aroma on the brain response to bread images in reward-related brain areas were compared (whole brain results in Supplementary Table 5), controlling for differences in aroma

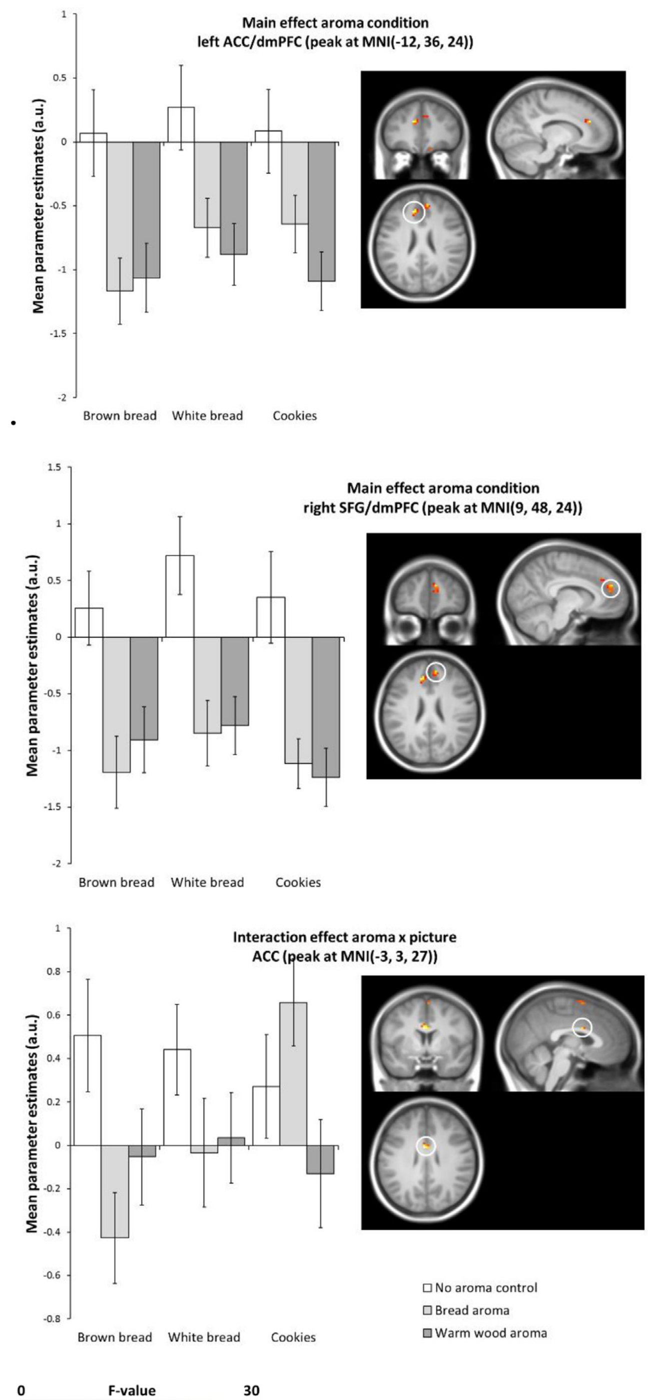

Fig. 4. Main effect of aroma on food cue reactivity in the dorsomedial prefrontal cortex and interaction between aroma and picture type in the anterior cingulate from the reward ROI analysis (mean ± SE parameter estimates for, see Table 5 for details).

Table 6
Results of the reward ROI factorial analysis with 2 aroma conditions and 3 picture types (n = 28).[1]

Brain region	Peak voxel coordinate (MNI)			Peak p_{fwe}	*F*-score
	X	*Y*	*Z*		
Main effect aroma					
R Dorsal putamen	24	0	12	0.02	23.2
	21	3	15	0.04	21.2
R Supplementary motor area	3	3	63	0.15[2]	23.5
Main effect picture type					
	–	–	–	–	–
Interaction aroma x picture					
Supplementary motor area	0	9	66	0.12[3]	23.5

[1] Flexible factorial model with Bread minus No aroma and Warm wood minus no aroma as aroma conditions. Shown are clusters in reward ROIs with a small-volume corrected peak $p_{fwe} < 0.05$.
[2] Cluster-level $p_{fwe} = 0.01$.
[3] Cluster-level $p_{fwe} = 0.03$. L = left, R = right hemisphere.

liking and intensity. Brown bread with bread compared to wood aroma tended to be associated with greater activation in the supplementary motor area (MNI(−12, 0, 63), ROI peak $pfwe = 0.065$, cluster-level $pfwe = 0.05$, Z = 4.24, k = 25). Whole-brain, white bread with bread compared to wood aroma activated different parts of the cerebellum, left lingual gyrus and left lateral OFC (Supplementary Table 5). There were no areas where wood aroma induced greater activation than bread aroma during exposure to bread images.

3.3. Behavioral versus fMRI results

3.3.1. Bread versus wood aroma

First, we explored whether the neural differences between bread and wood aroma (3.2.3) are reflected in the behavioral measures by correlating the average parameter estimates from the bread versus warm wood clusters with the differences in liking and wanting scores from the choice task session. There were only few and weak correlations (highest r-squared = 0.11), which did not survive correction for multiple testing.

3.3.2. Correlation with food choice task measures for brown versus white bread

There was a positive correlation between delta reaction time in the food choice task and brown bread vs white bread activation in the right superior temporal gyrus (MNI(63, −3, −3), z = 4.7, k = 51, $p < 0.05$ FWE-corrected, Fig. 6). Note that when the largest difference in reaction time was omitted the R^2 dropped from 0.74 to 0.30.

In addition, there were negative correlations between brown bread versus white bread image activation in the ventrolateral orbitofrontal cortex (OFC) and delta liking and wanting in the choice task session (delta liking: MNI(−30, 15, −24), z = 4.1, k = 28; delta wanting: MNI (−30, 18, −24), z = 4.4, k = 39; Fig. 7). This area was among the reward ROIs. Choice task outcomes did not correlate with brain activation by the images.

However, there was a positive correlation between the differences between choice frequencies of brown bread and cookies and right dorsolateral PFC activation (MNI(51, 39, 12), inferior frontal gyrus triangular part, k = 48, z = 4.3). Activation in this area also correlated positively with delta liking (BB-CK) (MNI(48, 39, 12), inferior frontal gyrus triangular part, k = 59, z = 4.95) and delta wanting (BB-CK) (MNI(51, 39, 12), inferior frontal gyrus triangular part, k = 69, z = 5.2), see Fig. 8.

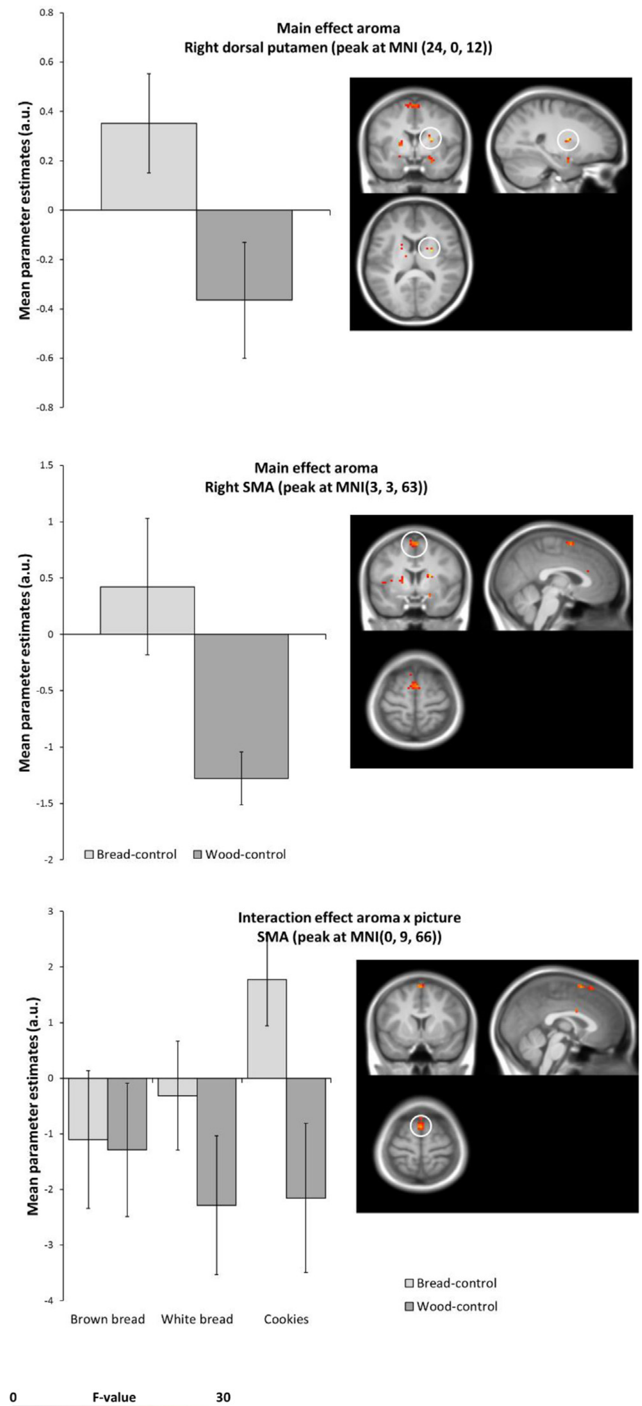

Fig. 5. Main effect of aroma on food cue reactivity in the dorsal striatum and main effect of aroma and interaction with product type in the supplementary motor area (SMA) in the reward ROI analysis (mean ± SE parameter estimates for the aroma versus the no aroma control condition, see Table 6 for details).

4. Discussion

4.1. Aroma effects on choice task behavior and brain responses to bakery food product cues

We investigated the effects of aroma on choice behavior and brain responses to bakery food product cues, i.e. the healthier brown bread, the less healthy white bread and cookies. Possible effects of congruent and incongruent aromas were tested as well. To our knowledge, we are to first to report on the effects of bread aroma on intended bakery

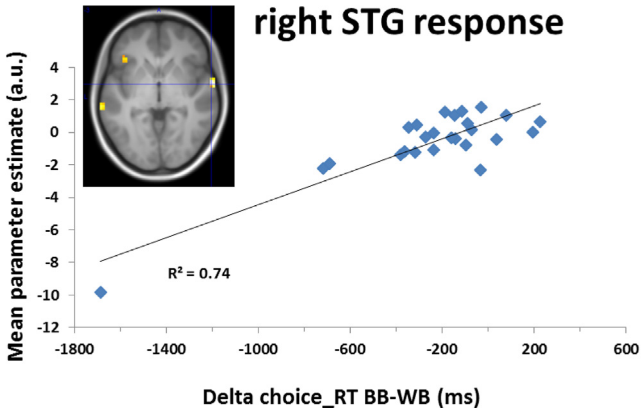

Fig. 6. Illustration of the positive correlation between the difference in reaction time between brown bread and white bread choices in the choice task (delta Choice_RT BB-WB) and brain activation in responses to brown versus white bread picture presentation in the right superior temporal gyrus (STG, peak at MNI(63, −3, −3)). Without the largest difference in reaction time $R^2 = 0.30$.

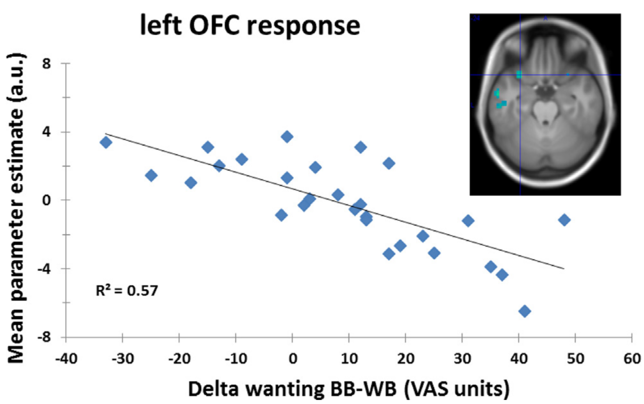

Fig. 7. Illustration of the negative correlation between the difference in wanting score between brown bread and white bread (delta wanting BB-WB) and brain activation in responses to brown versus white bread picture presentation in the left ventrolateral orbitofrontal cortex (OFC, peak at (MNI(−30, 18, −24)).

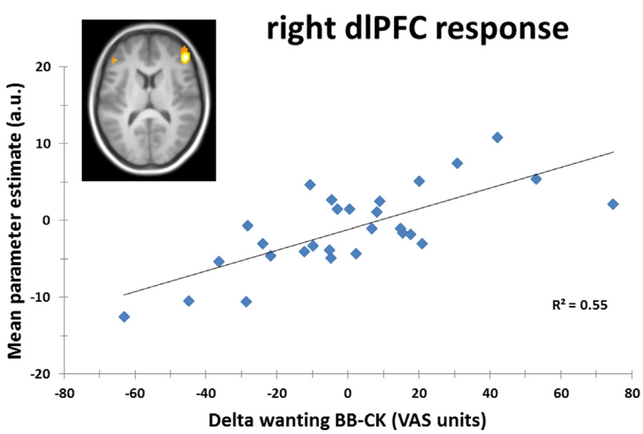

Fig. 8. Illustration of the positive correlation between the difference in wanting score between brown bread and cookies (deltaWanting BB-CK) and brain activation in responses to brown versus cookie picture presentation in the right dorsolateral prefrontal cortex (dlPFC, peak at MNI(51, 39, 12).

product choice, which so far appear to rely on an urban myth rather than actual (published) data.

Behavioral tests showed higher preference for images of brown bread, and also for images of cookies, compared to images of white bread. These effects were especially apparent in the food choice task where participants selected one product image out of two alternatives. Higher preference of brown bread over white bread was also observed previously in a supermarket study where brown bread (in this case wheat bread) outsold white bread by a large margin (de Wijk et al., 2016). Thus, behavioral and real-life supermarket data suggest that in the Netherlands brown bread is generally preferred over white bread. Interestingly, it has also been shown that people preferred refined bread to whole wheat bread when both were made using equivalent ingredients and procedures; the commercial samples of refined and whole wheat breads were liked equally well (Bakke & Vickers, 2007).

In contrast to the relatively large effects of product type, effects of aroma were virtually absent in the behavioral tasks, with the exception of the food choice task where aromas had differential effects on the choice of brown bread and cookies. Unexpectedly, brown bread images were selected more often with the incongruent, non-food aroma (wood) whereas images of cookies were selected more often with the incongruent bread aroma. This pattern was mimicked in anterior cingulate (ACC) responses of the brain imaging results: the ACC response to cookie images was significantly greater than that to images of brown bread in the bread aroma condition. In addition, the response to brown bread images during bread aroma exposure was smaller than that during control aroma (see below). Brain imaging also showed other effects of aroma. These unexpected results demonstrate that, at least in this study, interactions between aromas and images are not driven by their congruency.

The reward ROI factorial analysis on brain responses versus baseline showed significant deactivations in the bilateral dorsomedial PFC and right dorsal anterior cingulate for both aroma conditions. In line with this, in a direct whole-brain comparison controlling for aroma liking and intensity, we found greater activation in the bilateral dorsomedial PFC (including the dorsal anterior cingulate), right lateral OFC and left precentral gyrus during the no aroma control condition compared to the averaged aroma conditions. The dorsomedial PFC/anterior cingulate cortex activates during reward anticipation (Hoogendam et al., 2013; Knutson et al., 2001b). The pattern we observed may be due to heightened anticipatory brain activity at the time of stimulus onset in aroma but not in control blocks, since aroma delivery was cued with a red crosshair, resulting in a relative decline in activity upon aroma delivery.

An alternative explanation may be that the aroma-paired cues elicited greater attention, resulting in greater deactivation of the medial prefrontal cortex and ACC, which are part of the default mode network (DMN). This is one of the brain's resting state networks which is more active during 'rest' and becomes deactivated during task performance (Greicius, Krasnow, Reiss, & Menon, 2003; Raichle et al., 2001). The deactivation we observed during aroma + image presentation is in the medial PFC part of the DMN. Gilbert et al. found that medial PFC (de) activation may depend more on the requirement of a task for transformation and manipulation of internally represented information than on task difficulty, with greatest activity in situations predominantly requiring attention to perceptual information (Gilbert, Bird, Frith, & Burgess, 2012). Further, greater DMN deactivation has been suggested to reflect greater task engagement (Greicius & Menon, 2004). Thus, our finding of greater deactivation for bakery product images paired with aroma delivery might either reflect heightened anticipation preceding stimulus presentation or increased attention due to the presence of the aroma.

Surprisingly there was no greater activation to images with aroma versus no aroma. The reason for this may be that olfaction-related activation is less pronounced due to the concomitant visual stimulation, which may attract most attention.

In addition, there was a trend towards greater food cue responses in the presence of bread aroma compared to no aroma and warm wood aroma in the right amygdala. The amygdala is part of the appetitive brain network (Dagher, 2012) and has been reported to encode the salience of (food) stimuli (Arana et al., 2003; LaBar et al., 2001; Pelchat, Johnson, Chan, Valdez, & Ragland, 2004; Piech et al., 2009). In addition, it has been shown to encode stimulus intensity but not valence for aroma stimuli (Anderson et al., 2003; Royet, Plailly, Delon-Martin, Kareken, & Segebarth, 2003). This could explain the observed effect since the bread aroma was rated as more intense than the wood aroma. However, the amygdala response during wood aroma did not differ from that during no aroma, which makes it unlikely that this amygdala activation is driven by intensity differences. Thus, the most likely explanation is a higher salience of bakery product cues due to the bread aroma compared to no aroma and the incongruent (non-food) wood aroma.

As alluded to above, the ACC response to cookie images was significantly greater than that to brown bread images in the bread aroma condition. At the same time, the ACC response to brown bread during bread aroma was smaller than that during control aroma. The former mimics the finding of greater activation for cookie images during bread aroma in the SMA. The ACC is involved in response monitoring and action selection (Devinsky, Morrell, & Vogt, 1995) and the dorsomedial PFC/anterior cingulate cortex is thought to play a role in coding the motivational value of external events (Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Among others, it activates during reward anticipation (Hoogendam et al., 2013; Knutson et al., 2001b). The adjacent SMA is involved in approach and avoidance behaviors and performs motor preparation (Nachev, Kennard, & Husain, 2008). It also activates during reward anticipation (Knutson et al., 2001b; Knutson, Adams, Fong, & Hommer, 2001a). In our context of a cue exposure task, the observed ACC and SMA activation might suggest greater reward anticipation specifically for cookies in the presence of bread aroma. This is supported by the behavioral finding that images of cookies are selected more often in the presence of bread aroma. However, the correlation between choice task behavior measures and ACC and SMA activation was not significant.

4.2. Bread vs wood aroma

When looking at specific effects of aroma by subtracting the no aroma control condition we found that among the reward ROIs bread aroma was associated with greater activation than wood aroma in the right dorsal putamen and SMA. The dorsal striatum has been implicated in appetitive motivation and activates during presentation of both primary and secondary rewards (Balleine, Delgado, & Hikosaka, 2007). Our findings may thus be consistent with heightened appetitive motivation for products paired with bread compared to wood aroma. However, this effect on the neural level was not reflected in the behavioral data; there was no general effect of aroma type on product preference and no effect of aroma type on choice response times and liking and wanting ratings.

In a direct comparison, we observed greater activation during bakery product exposure in the left precentral gyrus and left dorsolateral PFC for bread compared to wood aroma, while controlling for differences in aroma liking and intensity. The precentral gyrus contains the primary motor cortex and is involved in preparing for and executing action. Greater precentral gyrus activation has been found in obese compared with lean participants in a meta-analysis on responses to foods and non-foods (Brooks, Cedernaes, & Schioth, 2013) and in children versus adults in response to unhealthy foods (van Meer et al., 2016). Furthermore, this area activates during reward anticipation (Kirsch et al., 2003; Wittmann et al., 2005) their motivational value (Brooks et al., 2013). This suggests that bread aroma elicits a greater motivational or motor response towards food products than the more incongruent wood aroma. A similar result was found when comparing the effects of bread and wood aroma on the brain response to bread images in reward-related brain areas, while controlling for differences in aroma liking and intensity; Brown bread with bread compared to wood aroma was associated with greater activation in the supplementary motor area. In line with the above this suggests greater reward anticipation for brown bread paired with bread aroma, i.e., the congruent combination.

The dorsolateral prefrontal cortex (dlPFC) has been implicated in top-down and cognitive control (Carter & van Veen, 2007), self-control during food choices (Hare, Camerer, & Rangel, 2009; Hare, Malmaud, & Rangel, 2011), and response inhibition (Simmonds, Pekar, & Mostofsky, 2008). In a food choice task, Hare et al. are found effects of perceived healthiness of food images in the left dlPFC, i.e., in a task which is better suited to engage inhibitory control processes than a cue exposure task like we used (Hare et al., 2011). However, there is evidence that food viewing can elicit activation of brain regions involved in inhibitory control (Bruce et al., 2010; Davids et al., 2010; Killgore et al., 2003; Smeets, Kroese, Evers, & de Ridder, 2013; Stice, Spoor, Bohon, Veldhuizen, & Small, 2008). More specifically, in a meta-analysis a concurrent cluster was found in the left dlPFC for high-energy versus low-energy food image viewing, albeit with only two contributing studies (van der Laan et al., 2011). These and our results could thus reflect engagement of cognitive control processes by food cues, which appears to be stronger for bread than for wood aroma, perhaps because the addition of bread aroma makes the food cue stronger since it is a food aroma, while wood aroma adds sensory stimulation but is incongruent. Again, these neural differences between bread and wood aroma were not reflected in any of the behavioral measures.

4.3. Associations between brain responses to bakery product cues and food choice task measures

There was a positive correlation between the difference in reaction time in the food choice task and brown bread versus white bread activation in the right superior temporal gyrus. Thus, participants who reacted faster to brown bread had lower activation in this area. An adjacent part of the right superior temporal cortex has previously been found to activate in sated individuals during choosing between low- and high calorie foods that were matched on visual characteristics and liking, suggesting that this area encodes biological relevance of food stimuli (Charbonnier, van der Laan, Viergever, Smeets, & Tregellas, 2015). The superior temporal cortex has also been implicated in attention and processing of salience by studies using food versus non-food commercials (Gearhardt, Yokum, Stice, Harris, & Brownell, 2014; Rapuano, Huckins, Sargent, Heatherton, & Kelley, 2016) and food logo's (Bruce et al., 2013), as well as in attention studies (Roberts & Garavan, 2013; Wild et al., 2012). Based on this, our results could reflect less attention for images of brown compared to white bread along with faster responses in the choice task. Thus, this may indicate that responses to brown bread require less consideration and are more habitual than those to white bread.

There were negative correlations between brown bread versus white bread image activation in the ventrolateral orbitofrontal cortex (OFC) and the difference in liking and wanting reported for these breads in the behavioral task. Thus, participants who liked and wanted white bread more than brown bread, resulting in a negative delta, had a stronger OFC response. Conversely, participants who preferred brown bread over white bread, resulting in a positive delta, had a weaker OFC response for brown bread compared to white bread. The OFC has been implicated in reward processing. Again, this might suggest a more habitual response to brown bread and a more goal-directed response to white bread (see Balleine and O'Doherty (2010) for a review on habitual versus goal-directed responding), which would align with our interpretation of the previous finding.

However, there was a positive correlation between the differences in choice frequencies of brown bread and cookie images and right dorsolateral PFC activation. Activation in this area also correlated positively with delta liking and wanting for images of brown bread versus cookies. Thus, individuals with a greater preference for images of brown bread than for cookies had greater dlPFC activation. As mentioned above, the dlPFC has been implicated in cognitive control and response inhibition (Carter & van Veen, 2007; Simmonds et al., 2008) and self-control during food choices (Hare et al., 2009, 2011). Van Meer found that children with a higher BMI had less activation in the left and right dlPFC in response to viewing more liked (unhealthy) versus less liked (healthy) foods (van Meer et al., 2016). These and our results suggest more engagement of cognitive control processes by brown bread compared to cookies in participants with a greater preference for brown bread over cookies. This would also imply that the preference for brown bread images observed in our behavioral tests, and the preference for brown bread in the supermarket study reported previously, is primarily determined by cognitive processes. An example of cognitive processes is a possible health consideration that make consumers choose brown bread over white bread. The HTAS results (Table 1), suggest that our participants were more pleasure than health oriented. Even though they may actually "want" white bread, they may rationally choose the more healthy choice for themselves (and others such as their family members). The longer reaction times to reject white bread in the behavioral choice tasks may be indicative for an internal competition between the initial drive to select white bread, and health considerations. These types of processes, i.e. processes determining choice between healthier or preferred food products, are difficult to capture with sensory tests. Sensory science does not provide insight in the motivation of choice behavior. This study demonstrates that neural measures may provide important additional insights into the nature of processes that drive consumer behavior.

4.4. Conclusion

In our study population, brown bread was preferred over white bread, as reflected in higher liking and wanting and shorter response times in a food choice task employing food images. Aromas showed moderate or incongruent behavioral effects that were limited to the choice task. Neural results provided additional insights; overall bread aroma may increase the salience of bakery products compared to no aroma and a warm wood aroma. Specifically, bread aroma induced greater activation for cookies in areas related to reward anticipation. Although in our choice task cookies were selected more often in the presence of bread aroma, this behavior did not correlate with the brain measures. The correlations between behavioral measures and brain responses suggest lower attention for and a habitual response to brown bread images and higher attention and a more goal-directed response to white bread images. The more habitual response to brown compared with white bread suggested by the neural data underscores that nudging towards the healthier choice using (bread) aroma may be challenging.

Acknowledgements

The use of the 3T fMRI facility has been made possible by Wageningen University & Research Shared Research Facilities. We thank Monique Zwinkels (Wageningen University) for her help in the fMRI data collection. In addition, we thank Graham Finlayson for providing the Leeds Food Preference Questionnaire.

Financial support

This project received financial support from the Dutch Bakery Centre and the Ministry of Economic Affairs (grant number AF12104 BO-24.06-001-004). Neither organization had any role in the design, analysis, or writing of this article.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodqual.2018.03.015.

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