Food Quality and Preference 85 (2020) 103959

Contents lists available at ScienceDirect

Food Quality and Preference

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

Smelling our appetite? The influence of food odors on congruent appetite, food preferences and intake

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ARTICLE INFO

Keywords:
Olfaction
Sensory-specific appetite
Eating behavior
Explicit exposure
Congruency
Macronutrients

ABSTRACT

We are surrounded by sensory food cues, such as odors, that may trigger (un)conscious decisions and even lead to (over)eating, it is therefore crucial to better understand the effect of food odors on behavioral responses. Food odor exposure has been shown to enhance appetite for food products with similar properties: sensory-specific appetite. This suggests that based on previous encounters with foods, we have learned to detect the nutritional content of foods, through our sense of smell. We investigated the influence of aware exposure of macronutrient-related odors on various measures of eating behavior, in a cross-over intervention study. Thirty two normal-weight healthy and unrestrained Dutch females took part in five test sessions. On each test session, they were exposed to one of five conditions (active smelling of clearly noticeable odors representing food high in carbohydrates, protein, and fat, low in calories, and a no-odor condition for 3-min) and assessed on specific appetite, food preferences and intake. Odor exposure increased congruent appetite after protein-related odor exposure. Similarly, protein-related odor exposure influenced the liking for protein foods and the preference ranking for savory products. However, food intake was not affected by smelling congruent food odors. Together this indicates that exposure to (aware) food odors may mostly influence appetite, but does not impact subsequent food intake. Moreover, appetite seems to be triggered by taste qualities rather than macronutrient information of the food, as signaled by olfactory cues. Future studies should investigate the role of awareness in more detail, to fully understand how odors might be used to steer people towards healthier food choices.

1. Introduction

Living in an obesogenic environment, we are surrounded by food (odor) cues that may trigger (un)conscious decisions and induce us to (over)eat (Bellisle, 2003; Boesveldt & de Graaf, 2017; King, 2013). Exposure to food cues may induce anticipatory physiological responses and may influence on our appetite and food intake (Proserpio, de Graaf, Laureati, Pagliarini, & Boesveldt, 2017; Wooley & Wooley, 1973). Olfaction plays an important role in eating behavior by detecting food, attracting our attention, and triggering our appetite (Boesveldt & de Graaf, 2017; Stevenson, 2010). However, the effect of food odors on subsequent behavioral responses is still not fully understood.

Olfaction may play a role in appetite and meal initiation (Yeomans, 2006; Zafra, Molina, & Puerto, 2006). Some studies have suggested that food cues exposure increases appetite for foods with similar properties and decreases for foods with dissimilar properties, known as *sensory-specific appetite* (SSA) (Ferriday & Brunstrom, 2011; Ramaekers et al., 2014; Ramaekers, Boesveldt, Lakemond, van Boekel, & Luning, 2014; Zoon, de Graaf, & Boesveldt, 2016). SSA may be generalized across foods within certain categories as taste and energy–density (Ferriday & Brunstrom, 2008, 2011; Ramaekers et al., 2014; Ramaekers et al., 2014; Zoon et al., 2016). A brief exposure to visual and odor cues of pizza showed an increase in desire to eat and prospective intake of pizza and savory food, and decrease for sweet food (Ferriday & Brunstrom, 2008, 2011). Similarly, Ramaekers et al. showed that suprathreshold active smelling (Ramaekers et al., 2014) and ambient exposure (Ramaekers et al., 2014) of sweet odors may enhance appetite for sweet foods and reduce appetite for savory foods, and *vice versa*. Moreover, Zoon et al. replicated these findings, and showed that actively smelling high-calorie odors could increase appetite for high-calorie food and decrease appetite for low-calorie food, and *vice versa* (Zoon et al., 2016). Taken together, it seems that based on previous experiences, we have learned that food odor cues may convey information related to the taste quality or caloric content of the associated food. This information may even signal the composition of the food in terms of macronutrient content and thereby induce congruent appetite to facilitate specific physiological responses and potentially steer towards congruent actual food intake (Berthoud, Münzberg, Richards, & Morrison, 2012; Boesveldt &

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https://doi.org/10.1016/j.foodqual.2020.103959
Received 25 November 2019; Received in revised form 17 March 2020; Accepted 12 April 2020
Available online 22 April 2020

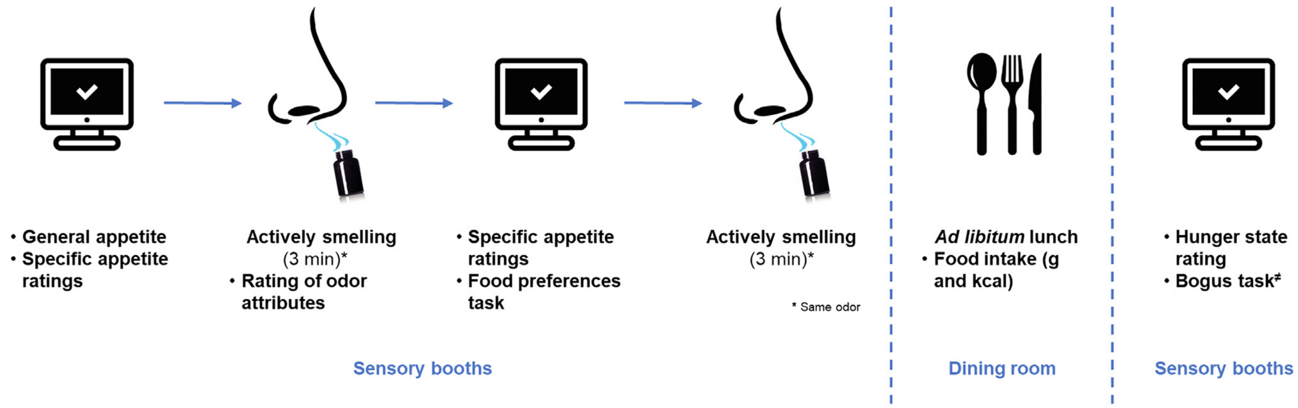

Fig. 1. Procedure for each test session. ≠The bogus task (alertness task) was performed as part of the alternative goal for keeping participants naïve from the actual aim of the study.

de Graaf, 2017; McCrickerd & Forde, 2016; Ramaekers et al., 2014; Smeets, Erkner, & de Graaf, 2010; Zoon et al., 2016). Research to date has not yet investigated if food odors that signal macronutrient content may impact congruent appetite and food intake.

Moreover, contradictory findings have been shown between the influence of odors on appetite versus actual food choice and intake depending the level of awareness of the odor exposure. Studies with conscious and detectable ambient odors have shown an influence on self-reported appetite (Ferriday & Brunstrom, 2011; Ramaekers et al., 2014), but not on food preference and intake (Zoon, He, De Wijk, Graaf, & Boesveldt, 2014). Conversely, other studies suggested that non-conscious exposure to ambient odors, also known as priming, could lead towards selecting congruent foods (Chambaron, Chisin, Chabanet, Issanchou, & Brand, 2015; de Wijk & Zijlstra, 2012; Gaillet, Sulmont-Rossé, Issanchou, Chabanet, & Chambaron, 2013; Gaillet-Torrent, Sulmont-Rossé, Issanchou, Chabanet, & Chambaron, 2014). Overall, findings suggest that (un)conscious odor stimulation may play a crucial role in the (type of) response it exerts (McCrickerd & Forde, 2016; Smeets & Dijksterhuis, 2014).

Very little is currently known about the impact of food odors that signal specific nutrient information on various measures of congruent eating behavior within the same participants. Therefore, in the present study we aimed to investigate how actively smelling odors that signal macronutrients would impact specific appetite, food preferences and intake in unrestrained normal-weight females. We hypothesized that appetite would be higher for food products upon the exposure of congruent food odors compared to incongruent food odor (e.g. exposure to carbohydrate-related odors will increase specific appetite for carbohydrate-rich foods, such as bread or pasta, compared to incongruent products as meat (protein), cream (fat), melon (low-energy), etc.). However, this specific appetite may be overruled by cognitive factors (such as knowledge of post-ingestive effects of the foods, previous meals, specific health goals or eating habits), and not necessarily lead to similar food preferences and intake.

2. Materials and methods

2.1. Participants

Statistical power was calculated based on previous research (Chambaron et al., 2015; Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Proserpio et al., 2017; Ramaekers et al., 2014; Zoon et al., 2016) and led to 32 participants. Normal-weight Dutch females between 18 and 35 years old were recruited from Wageningen and surroundings. Inclusion criteria consisted of: a normal sense of smell (scoring ≥12 on the 16 items Sniffin' Sticks odor identification test (Oleszkiewicz, Schriever, Croy, Hähner, & Hummel, 2019)); self-reported normal sense of taste; being an unrestrained eater (score < 3.40, out of a maximum of 5), on the Dutch Eating Behavior Questionnaire, DEBQ (van Strien, Frijters, Bergers, & Defares, 1986); correct identification of the used odors by means of a multiple forced-choice task; odor-label association ('How well do you think this smell corresponds to *[specific label]*?') and liking for the food odors and products used in the study (> 40 on 100 mm VAS). Participants were excluded when they were: smokers; had any dietary restriction towards specific foods (self-imposed or otherwise; e.g. vegetarian, vegan); used medication other than paracetamol and hormonal contraceptives; were pregnant or had the intention to become pregnant during the experiment or were currently breastfeeding; or reported weight loss or weight gain of more than 5 kg or following a special diet in the two months prior to the study.

Potential participants provided written informed consent at the start of the screening session. After analyzing the data from the screening session, a total of 32 unrestrained females (DEBQ: restrained score of 2.6, SD = 0.7, range 1.1–3.3) with an average age of 21.9 year (SD = 2.2), average BMI of 21.6 (SD = 1.6) kg/m^2, and normal sense of smell (odor identification score of 13.3, SD = 1.2, range 12–16) were included in the study. They received monetary compensation for their contribution. The study was conducted in accordance with the Declaration of Helsinki (revised in 2013) and approved by the Medical Ethical Committee of Wageningen University (NL66580.081.18).

2.2. Procedure

In a cross-over study design encompassing five test sessions, participants were exposed to three macronutrient-related odors (carbohydrates, proteins and fat), a low-calorie odor, and a no-odor control condition. On each test session, participants were exposed to either one of the two odors of a certain category (see Section 2.3- Odor stimuli for further details). The same odor was presented twice to the participants during the test session (Fig. 1). Each participant was randomly assigned to a unique sequence of odors. Test sessions took place around lunch time (11.30–14.00). Participants attended all test sessions at the same time of the day, with at least two days in-between sessions. Participants were asked not to eat or drink anything, apart from water, at least 3 h before testing. An alternative goal ('To investigate the role of different odors on alertness') was formulated to keep participants naïve for the actual aim of the study, to avoid influences of cognitive factors and participants' expectations on study outcomes.

Upon arrival, participants were asked to rate their general and specific appetite in isolated sensory booths. Then, they received a bottle containing an odor stimulus and were instructed to smell the odor and rate it on several attributes. Next, they were instructed to hold the bottle under their nose and breathe normally for 3 min. After odor exposure, they rated their specific appetite and performed a computer-based task on food preferences. Subsequently, they received the same odor stimulus again to smell for 3 min with similar instructions. Thereafter, participants were escorted to a dining room where they were could select lunch from a salad bar to covertly measure *ad libitum* food intake. After participants finished their lunch, they were escorted back to the sensory booths to assess their general appetite and perform a bogus task to measure alertness (Psycho Vigilance Test, PVT (Basner & Dinges, 2011)). Participants followed instructions via an online questionnaire using EyeQuestion® (Version 3.11.1, Logic8 BV). On the last test session, participants were asked to complete a final questionnaire on the aim of the study. Then, they were debriefed. The procedure for each test session is shown in Fig. 1.

2.3. Odor stimuli

Odor stimuli encompassed a selection of 8 odors that represented foods differing in macronutrient composition (i.e. high in carbohydrates, protein, fat, or low-calorie). The selection of odors was based on the nutritional value of their food counterpart: at least 50% of total energy of the food should be derived from the specific macronutrient category, and low-calorie products should contain no more than 60 kcal/100 g (de Bruijn, de Vries, de Graaf, Boesveldt, & Jager, 2017; RIVM, 2016). Based on this and our previous study (Morquecho-Campos et al., 2019), two odors of each category were selected: corn (Symrise 653316; 0.8% in demineralized water, DW) and bread (Symrise 205361; 9% in propylene glycol, PG) for carbohydrates; duck (Symrise 619322; 0.4% in PG) and chicken (IFF 10913579; 0.06% in DW) for protein; butter (IFF 10922603; 0.5% mixed with diacetyl from Sigma-Aldrich; 0.01% in PG) and cream (IFF 10923144; 10% in PG) for fat; cucumber (IFF 15311331; 100%) and melon (IFF 15025874; 2% in PG) for low-calorie foods; and an odorless control (100% PG). Participants were counterbalanced exposed only to one odor per category. Odor stimuli (15 mL) were placed in (randomly-coded) brown 50 mL glass bottles. Odor stimuli were prepared at least one day before the experiment and stored in a refrigerator (4 °C) until the morning of the test session. Odor stimuli were taken out of the refrigerator to reach room temperature on the morning of each test session.

2.4. Measurements

2.4.1. Odor attribute ratings

Each odor was assessed on the attributes of liking, intensity, familiarity, intention to eat a product with that odor, and mouth-watering sensation on a 100 mm visual analog scale (VAS) anchored by "Not at all" to "Very much". Then, participants were asked to identify the odor among a list of food products including 'no-odor' by a multiple forced-choice task ('Which of the following labels best fits the odor?'). Afterwards, odor-label association was assessed by 'How well do you think this smell corresponds to *'[specific label]'* on a 100 mm VAS. Ratings for the odors can be found in the supplementary materials (Table S1).

2.4.2. General and specific-sensory appetite

General appetite was determined by assessing hunger, fullness, prospective consumption, desire to eat, and thirst on 100 mm VAS. Specific appetite was assessed by rating 'How much would you like to eat *'[specific product]'* at this moment?' on a 100 mm VAS anchored by "Not at all" to "Very much". Specific products consisted of 12 food items (3 per macronutrient category), that either did or did not match the odor stimuli (congruent/incongruent): pasta, bread, and corn for carbohydrates; chicken, tuna, and meat for protein; bacon, nuts, and cheese for fats; cucumber, tomato, and melon for low-calorie food products.

2.4.3. Food preferences

Food preferences were measured by means of the Macronutrient and Taste Preference Ranking Task (MTPRT) (de Bruijn et al., 2017), ran on E-prime (E-Prime 2.0, Psychology Software Tools, Pittsburg, PA). This validated computer-based task consists of 3 parts: practicing, liking and ranking. The practicing part is meant to familiarize the participants with the ranking part. The liking and ranking part used 32 food pictures which consisted of four macronutrient categories (food products rich in carbohydrates, protein, fat, and low-calorie); each category consisted of 4 sweet and 4 savory food products; except for the protein category for which the 8 products were savory food products. The 32 food pictures are different from the ones used in the practicing part. After the practicing part, the participants rated their liking of the 32 food products ("How much do you like *[specific food product]?"* on a 100 mm VAS, anchored by "Do not like at all" to "Like extremely"; a picture of the food product was displayed below the liking question on the screen). Liking ratings were aggregated per macronutrient and taste category for analyses. The ranking part consisted of 2 sections: pictures of foods representing macronutrient categories (high-carbohydrates, high-protein, high-fat, and low-calorie; 16 different combinations), and taste categories (sweet and savory taste; 24 different combinations). In each combination, the screen displayed 4 different pictures (1 per category in the macronutrient section and 2 per category in the taste section). Participants were asked to rank the food products depending on their desire to eat at that moment. The order and screen position of the food pictures were randomly displayed and balanced across trials. Macronutrient and taste preference scores were calculated as described in de Bruijn et al. (2017). Macronutrient preference scores can range between 1 and 4 (the total score divided by the 16 times a food product from each category was displayed), with higher scores indicating a higher preference. Taste (savory or sweet) preference scores can range from 1.5 to 3.5 (the total score divided by the 24 times a food product from both categories were displayed). Due to the nature of the ranking part, sweet and savory scores are opposite to each other, therefore we only report savory taste preference scores.

2.4.4. Food intake

The *ad libitum* lunch consisted of a salad bar that contained 8 toppings (2 options per macronutrient: carbohydrates, protein and fat, and 2 low-calorie products), lettuce as base and (optionally) 28 g of salad dressing. The selection criteria for the toppings was the same as for the odor stimuli: at least 50% of the total energy of a food product should be derived from the corresponding macronutrient category, while toppings representing the low-calorie category contained no more than 60 kcal/100 g. Table 1 shows the food products per category, calories and percentages of each macronutrient. All food products were regular products that are commercially available to consumers in a

Table 1
Food products offered at the *ad libitum* lunch.

Category	Food	Energy (kcal/100 g)	Carbohydrates (%)	Protein (%)	Fat (%)
Carbohydrates	Croutons	455	**57.1**	11.4	29.7
	White pasta	142	**78.0**	14.4	5.7
Protein	Ham strips	115	1.0	**69.6**	27.4
	Chicken strips	110	12.7	**72.7**	16.4
Fat	Mixed nuts	674	2.6	12.6	**82.5**
	48 + Gouda cheese	375	0.0	25.6	**74.4**
Low-calorie	Cucumber	12	63.3	20.0	15.0
	Cherry tomatoes	30	53.3	12.0	24.0
Base	Lettuce	15	29.3	34.7	18.0
	Dressing	40	95	0.1	2.3

Numbers in bold highlight the largest percentage of the total energy of the food product, which are related to their corresponding food category.

supermarket. Participants were instructed to build their own salad (with lettuce as a base) by choosing as many toppings and amount as they wanted. Participants were not allowed to go back to the buffet area or refill their plate once they started eating. Only one participant was allowed in the buffet area at any one time. They were instructed to sit in the dining area and to eat until they felt comfortably satiated, and were not obliged to finish their plate. The setting of the dining area was organized in order to refrain participants from facing the buffet area. The buffet was continuously refilled, to ensure a consistent presentation volume. Food intake was covertly measured by weighing the trays which contained each topping and lettuce before and after each participant 'built' their salad and by weighing the remaining amount on the plate of the participants after eating. Additionally, they received a glass of water (150 mL) that they were instructed to finish during the lunch.

2.5. Statistical analyses

Data are shown as mean and standard errors, unless otherwise specified. Results with a p value lower than 0.05 were considered statistically significant. All statistical analyses were carried out in RStudio (RStudio Team., 2016), and graphs were made using GraphPad Prism 5.0 (GraphPad Prism Software).

All analyses consisted of linear mixed models, carried out using the *lme4* statistical package in R (Bates, Mächler, Bolker, & Walker, 2015). The best fitting models were selected on the basis of parsimony. Necessary assumptions for mixed models were checked for each model. Post-hoc tests with a Bonferroni correction were performed given significant main or interaction effects, using the *lsmeans* statistical package (Lenth, 2016). Data were pooled over the 2 odors of the same category as described in the section 'Odor stimuli' (e.g. data resulting from exposure to 'bread' and 'corn' odor were collapsed into a 'carbohydrates' category) resulting in a variable labeled as 'odor category'.

Odor attribute ratings were analyzed as a dependent variable, with odor category as fixed effects and participants as random effects and shown in Table S1 of the supplementary materials.

Moreover, a variable 'awareness of the true study aim' was computed based on the results from the debriefing. This variable was added to all the models to test if the awareness of the true study impacts our different outcomes. This variable and other potential covariates that were not significant different were removed from the final models.

2.5.1. Sensory-specific appetite

Appetite data were labeled as congruent/incongruent, depending on the food products used relative to the odor condition. For example, specific appetite of carbohydrate-rich products (such as pasta, bread or corn) were considered congruent after exposure to a carbohydrate-related odor (bread or corn odor) but labeled as incongruent after exposure to other odor categories. Change in specific sensory appetite (SSA; difference in the specific appetite ratings before and after odor exposure) was analyzed as dependent variable. Odor category, (in)congruency of food product, and their interaction were included as fixed factors, participants were included as random factors, and general appetite ratings (hunger, fullness, prospective consumption, desire to eat and thirst were added individually), individual odor attribute ratings, specific appetite before odor exposure and liking of food products (as assessed during the screening session on a 100 mm VAS) were included as potential covariates. Due to this congruency variable, as there are no food products congruent with the no-odor condition, this condition was removed from the dataset when running the models. Results from the no-odor condition, descriptive statistics and statistical analyses, were reported using food product category as fixed factor. Covariates mentioned above were also used in this model.

2.5.2. Food preferences

For the liking and ranking results of the macronutrient part, congruency was similarly determined by the match between odor exposure category and each macronutrient preference score analyzed. For example, when analyzing preference score for carbohydrates, only exposure to carbohydrate-related odors was considered congruent, all other odor exposure conditions were incongruent. Each macronutrient preference score was analyzed as dependent variable in separate linear mixed models. Congruency and participants were included as fixed and random factors, respectively. For these models, the no-odor condition was removed from the dataset. Data from exposure to the no-odor condition are included in descriptive statistics.

For the liking and ranking results of the (savory) taste part, odor category and participants were included as fixed and random factors, respectively.

General appetite ratings, individual odor attributes ratings, and liking of the food products, aggregated across food product category, were entered as potential covariates in both macronutrient and savory taste preferences score's models.

2.5.3. Food intake

In a first model, total food intake, in g and kcal, was analyzed as dependent variable in separate linear mixed models. In a second model, odor category, congruency (depending on the food products selected and eaten relative to the odor condition) and their interaction were included as fixed factors. In a third model, odor category, food product category, and their interaction were included as fixed factors. For all the models, participants were included as random factors, and general appetite ratings, individual odor attributes ratings, and liking of food products (as assessed during the screening session on a 100 mm VAS) were included as potential covariates.

3. Results

3.1. Sensory-specific appetite

The main effect of congruency $F(1,1494) = 18.74$, $p < 0.0001$) was significant, suggesting sensory-specific appetite. Additionally, the effect of odor category was significant $F(3,1508) = 9.52$, $p < 0.0001$, and there was a significant interaction between odor category and congruency, ($F(3,1494) = 9.96$, $p < 0.0001$, Fig. 2**,** mixed model included odor familiarity, liking of the food product and specific appetite before odor exposure as covariates). Post-hoc tests revealed that the change in specific appetite for (congruent) protein-rich food products after smelling protein-related odors was significantly higher compared to incongruent food products. However, for the other odor categories (carbohydrates, fat and low-calorie) there was no significant difference in change in appetite between congruent and incongruent

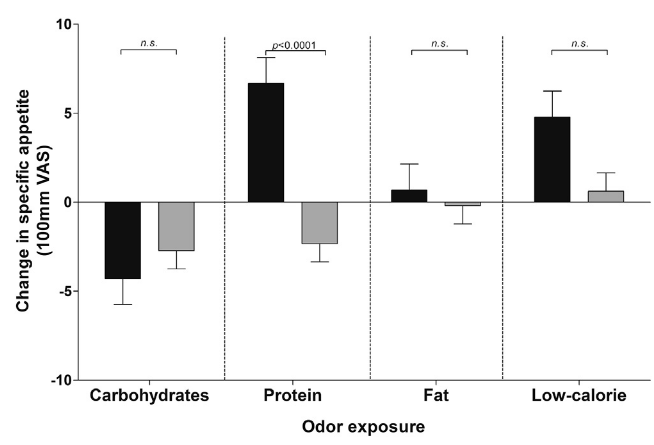

Fig. 2. Change in specific appetite upon odor exposure for congruent (black color) and incongruent food products (light gray color) for the different odor categories. Values are expressed as mean and standard error.

food products after odor exposure.

Exposure to no-odor did not affect the change in specific appetite for any of the food product categories ($F(3,347) = 0.67$, $p = 0.57$; mixed model including liking of food products and specific appetite before odor exposure as covariates); change in specific appetite by food product category (mean ± SE) = 0.31 ± 1.21 for carbohydrates, −0.60 ± 1.21 for proteins, −0.90 ± 1.20 for fat, and 0.80 ± 1.21 for low-energy products.

3.2. Food preferences

3.2.1. Macronutrient preferences

Exposure to protein-related odors significantly increased liking for congruent compared to incongruent food products ($F(1,94) = 4.51$, $p < 0.05$; Table S2). However, exposure to other odors did not influence liking for their congruent food products ($F(1,94) = 1.92$, $p = 0.17$ for carbohydrates; $F(1,94) = 0.29$, $p = 0.59$ for fats; $F(1,92) = 0.26$, $p = 0.62$ for low-calorie; all statistical models did not included any covariate, with the exception of the low-calorie model, where odor intensity and odor-label association were included as covariates; Table S2).

Exposure to congruent odors did not affect the subsequent preference ranking for corresponding macronutrients ($F(1,94) = 0.05$, $p = 0.83$ for carbohydrates; $F(1,94) = 0.94$, $p = 0.34$ for proteins; $F(1,94) = 1.22$, $p = 0.27$ for fats; $F(1,94) = 1.15$, $p = 0.29$ for low-calorie; no covariates were included in these models; Table S2).

3.2.2. Savory taste preferences

Odor exposure did not influence the liking for savory-tasting food products ($F(4,122) = 0.91$, $p = 0.46$; savory liking ratings upon protein-odor exposure 65.6 ± 1.63; carbohydrates 65.2 ± 1.64; fat 64.8 ± 0.05; low-calorie 64.5 ± 1.63; no-odor 64.2 ± 1.63).

However, odor exposure did influence the ranking savory-tasting foods ($F(4,122) = 3.66$, $p < 0.01$; mixed model with odor familiarity and liking of the savory food pictures used in the task as covariates): savory products were significantly higher ranked upon exposure to protein-related odors compared to fat-related odors and the no-odor condition (ranking score after protein-odor exposure 2.35 ± 0.05; low-calorie 2.29 ± 0.05; carbohydrates 2.28 ± 0.05; fat 2.23 ± 0.05; no-odor 2.21 ± 0.05).

3.3. Food intake

Firstly, total food intake (in g and kcal) did not significantly differ between conditions ($F(4,124) = 0.16$, $p = 0.99$, for g; $F(4,124) = 0.13$, $p = 0.97$, for kcal; Table S3; any covariate contributed to the fit of the model). Secondly, total food intake of congruent and incongruent food products (in g and kcal) was not significantly different after odor exposure ($F(1, 990) = 0.34$, $p = 0.56$ for g; $F(1, 990) = 0.39$, $p = 0.53$ for kcal; both mixed models including liking of food products as covariate). Lastly, there was no interaction between odor category and food product category ($F(9,976) = 0.11$, $p = 0.99$, for g; $F(9,976) = 0.21$, $p = 0.99$, for kcal; Fig. 3; both mixed models including liking of food products as covariate). The consumption of each food product category was similar after each odor exposure. As shown in Fig. 3A, the amount in grams of low-calorie products were significantly higher compared to carbohydrates, protein and fat ($F(3, 988) = 74.55$, $p < 0.0001$). On the other hand, the caloric intake of fat products was significantly higher compared to the other food product categories ($F(3, 988) = 125.56$, $p < 0.0001$; Fig. 3B).

3.4. Debriefing

In an open-question, participants were asked what they believed the true study aim was. Half of the participants mentioned the alternative goal (influence of odors on alertness) as the study aim, while the other half indicated something related to the influence of odors on eating behavior.

4. Discussion and conclusion

4.1. Discussion

Our aim was to determine the influence of aware exposure to macronutrient-related odors on various measures of eating behavior. Our results show that only protein-related odors influenced congruent appetite and liking. Odor exposure did not affect actual food intake.

The increase of congruent appetite upon odor exposure could be a direct sign of the body to activate specific metabolic routes for the smelled (macro)nutrient that is about to be ingested (Mattes, 1997; Nederkoorn, Smulders, & Jansen, 2000). Previous studies demonstrated sensory specific appetite (SSA) after exposure to taste (sweet/savory) and calorie related (high/low-calorie) food odors (Ramaekers et al., 2014; Ramaekers et al., 2014; Zoon et al., 2016). Based on these results, we hypothesized that humans are able to detect the nutritional content of foods, such as macronutrients, via their sense of smell (Boesveldt & de Graaf, 2017; Ramaekers et al., 2014; Zoon et al., 2016). However, our current results show that SSA was mainly driven by protein-related odors. Due to the nature of protein, this food category only represented savory tasting products. Moreover, since most foods we encounter in daily life are a complex mix of (macro)nutrients, this may weaken the link between sensory signals (taste and odor), food and its nutrients (Martin & Issanchou, 2019; Van Langeveld et al., 2017) and thereby minimize the specific appetizing effect of macronutrient-related odors. Taking this knowledge together, we postulate that olfactory SSA is perhaps mainly driven by taste quality (sweet/savory) of the food that the odor represents, rather than its macronutrient content. Protein-related odors may have increased congruent appetite largely for its savory taste rather than its macronutrient (protein) content. This taste association was also shown in the food preference results: exposure to protein-related odors increased the liking for protein food products compared to other food products and, similarly, the preference ranking for savory products. Surprisingly, protein-related odors did not influence the liking for savory food products nor preference ranking for food products rich in proteins. We could speculate that the sense of smell may be effective in protein-sensing in foods, as humans may be more prone to recognize and seek for sources of this particular nutrient –compared to other macronutrients– that is crucial for body maintenance (Carreiro et al., 2016).

According to our expectations and in line with previous studies, odor exposure did not influence actual food intake. Active sniffing and explicit odor exposure has been shown to affect specific appetite (Ferriday & Brunstrom, 2011; Ramaekers et al., 2014; Zoon et al., 2016); while passive and implicit odor exposure affected food choice (Chambaron et al., 2015; Gaillet et al., 2013; Gaillet-Torrent et al., 2014; Proserpio et al., 2017) and intake (Proserpio et al., 2017). Moreover, a recent study showed an influence of implicit odor exposure on attentional processing of visual food cues, but this effect vanished upon explicit odor exposure (Mas, Brindisi, Chabanet, Nicklaus, & Chambaron, 2019). The appetite ratings used in the current study (VAS scores) are explicit measurement that could be affected by conscious interaction with the environment, such as awareness of exposure to a specific odor, that may result in active cravings and deliberations whether or not to choose and eat that product. Conversely, the selection and intake of food from the buffet could be considered implicit measurements that might be more influenced by non-conscious cues and are governed by emotional, impulsive, automatic decision-making and reward responses (Cohen, 2008; Kahneman, 2011; Marteau, Hollands, & Fletcher, 2012; Mas et al., 2019; Rolls, 2011).

Even though food intake was measured within our lab facilities, we used an *ad libitum* salad buffet setting to mimic a more realistic eating environment. We offered two toppings per macronutrient category,

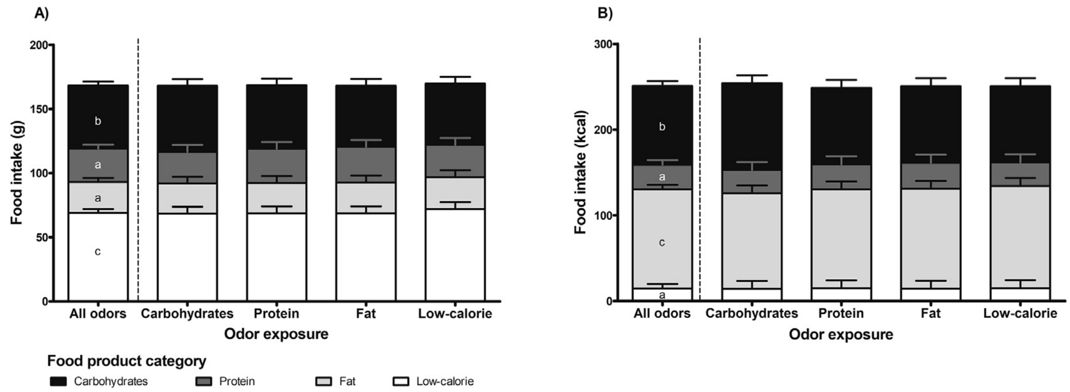

Fig. 3. Intake of food product categories in g (A) and kcal (B) across all odors and upon the exposure of each odor. Values are expressed as mean and standard error. Similar letters indicate no significant differences ($p > 0.05$) and are in ascending order (a = lowest value and c = highest value).

however it is worth noting that participants seemed to follow certain strategies, even though all food products were evaluated as moderate-highly liked (60–80 on a 100 mm VAS): 1) some participants took pasta (carbohydrate) as base of their salad instead of lettuce; 2) only one topping of the protein category was selected (chicken being the preferred one); 3) while for fat and low-calorie toppings, both options were chosen in similar amounts. This could indicate that participants built their salad according to certain habits based on their previous experiences and likings, expectations on the satiation value of each topping, and dietary patterns (Birch, 1999; Köster, 2009), leading to an overall static pattern, regardless of the odor they were exposed to. Some researchers have suggested that decision-making processes depend on the type of food, such as a full meal versus desserts or snacks (de Wijk et al., 2018; Wang, Cakmak, & Peng, 2018), where the latter two could be considered as discretionary calories and linked to reward and impulsive behavior while decision on a full meal is likely more habit-based. Other scenarios, such as performing the study ~~with~~ in a food choice environment such as a true buffet with several assortment of meals or snacks to choose from could be more sensitive to detect impulsive eating behavior, driven by external cues rather than habits. Nevertheless, Mors and collaborators did not find an influence of olfactory priming on food choice even though the buffet was performed in a real restaurant (Mors, Polet, Vingerhoeds, Perez-Cueto, & de Wijk, 2018). Further research should consider the use of other settings in which impulse buying is more common, such as supermarkets or convenience stores, as well as apply more implicit outcome measurements, e.g. eye-tracking, to assess food choices. These could provide more detailed and relevant information regarding real-life food appetite and selection upon odor exposure (Marteau et al., 2012; Wang et al., 2018). The potential influence of odor priming on healthier snacks or impulse buying rather than meal habits could have a greater impact in the prevention of weight gain and further healthier lifestyle.

A strong point of the current study is our cross-over design which takes into account individual characteristics that may affect differences in odor perception or eating behavior. Furthermore, in our previous research (Morquecho-Campos et al., 2019) we optimized the selection of odors and foods for the Dutch population since the identification of macronutrients is likely related to familiarity with certain foods and thus depends on cultural culinary experiences, and these may interfere with the mental representations associated to the odors. Despite these efforts, it cannot be ruled out that the odors did not strongly signal the intended macronutrient content and therefore weaken the expected effect on eating behavior.

A potential limitation is that about half of the participants inferred that our real aim was related to the influence of the odor exposure on appetite and/or food choice and intake. However, adding this variable to our statistical models did not modify the outcomes. Moreover, since our population only included unrestrained, normal-weight participants, the current findings cannot be generalized to other groups. Some studies have shown that individual differences in dietary restraint and body weight are decisive in the reactivity towards food. Restrained eaters (or overweight) tend to have a greater appetite and intake response upon being explicit exposed to food cues compared to unrestrained eaters (or normal-weight participants) (Coelho, Jansen, Roefs, & Nederkoorn, 2009; Fedoroff, Polivy, & Herman, 2003; Ferriday & Brunstrom, 2011; Tetley, Brunstrom, & Griffiths, 2009).

4.2. Conclusion

Aware exposure to protein-related food odors increases congruent appetite, demonstrating sensory-specific appetite. Odor exposure may trigger specific appetite based on the taste qualities of its associated food rather than its macronutrient content. Moreover, aware exposure to macronutrient-related food odors did not affect actual food intake. Further work should focus on the impact of unaware odors on eating behavior. Moreover, the use of implicit and more naturalistic measurements should be considered to further investigate the influence of olfactory cues on food intake.

Funding

This work was financially supported by the National Council on Science and Technology of Mexico (CONACyT) awarded to PMC.

CRediT authorship contribution statement

Paulina Morquecho-Campos: Conceptualization, Methodology, Resources, Investigation, Formal analysis, Writing - original draft. **Kees de Graaf:** Methodology, Supervision. **Sanne Boesveldt:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to thank IFF and Symrise for supplying the odors. We would like to specially acknowledge Arabella K. Ellenbroek for her assistance in data collection and analyses. Additionally, we would like to thank Els Siebelink, Henriette Fick-Brinkhof, Corine Perenboom, and Anne van de Wiel for sharing their expertise with us and for their support during the preparations and data collection of this study.

Deepest thanks to Dr. João Caldas Paulo for her insights during data analyses.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2020.103959.

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