9888 *J. Agric. Food Chem.* **2009,** *57,* 9888–9894
DOI:10.1021/jf901445z

JOURNAL OF
AGRICULTURAL AND
FOOD CHEMISTRY
ARTICLE

Retronasal Aroma Release and Satiation: a Review

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In view of the epidemic of obesity, one of the aims of the food industry is to develop good-tasting food products that may induce an increased level of satiation, preventing consumers from overeating. This review focuses on the possibility of using aroma as a trigger for inducing or increasing satiation. Using a novel approach of atmospheric pressure chemical ionization−mass spectrometry (APcI-MS) in combination with olfactometry, the relative importance of different aroma concepts for satiation was studied, from both consumer and food product points of view. The extent of retronasal aroma release appears to be a physiological feature that characterizes a person. Although the extent of retronasal aroma release appears to be subject specific, food product properties can be tailored in such a way that these can lead to a higher quality and/or quantity of retronasal aroma stimulation. This in turn provokes enhanced feelings of satiation and ultimately may contribute to a decrease in food intake.

KEYWORDS: Retronasal aroma stimulation; flavor; satiation; APcI-MS; MS-nose; olfactometry

AROMA PERCEPTION

Orthonasal versus Retronasal Olfaction. Aroma stimuli can reach the olfactory epithelium through two pathways: via the nose, during sniffing (referred to as orthonasal olfaction), and via the mouth, during food consumption (referred to as retronasal olfaction) (*1*).

Orthonasal olfaction processes stimuli from the external environment, which travel through the anterior nares toward the olfactory mucosa during sniffing. In contrast, during oral processing and after swallowing, volatile aroma molecules are released from the food matrix, and they reach the nasal cavity through the pharynx, stimulating receptors in the olfactory cleft. This pathway for aroma perception is defined as retronasal olfaction (**Figure 1**).

Differences in air flow patterns through the two pathways and aroma absorption across the mucosa may determine differences in ortho- and retronasal aroma perception (*1*, *3*, *4*). For example, differences in perceived aroma thresholds (*5*), cross-modal interactions of aroma and texture (*6*, *7*), and neural aroma processing (*2*) are reported to account for perceptual differences in ortho- and retronasal olfaction. Orthonasal aroma thresholds are observed to be significantly lower than retronasal aroma thresholds. Correspondingly, the concentration of aroma reaching the olfactory cleft through the retronasal pathway is usually much higher than during orthonasal perception of aromas due to salivation, warming, and mastication during food consumption (*5*).

Aroma stimuli have also been shown to increase the intensities of perceived thickness and creaminess, but only when the (butter) aroma was presented retronasally (*7*). This enhancement is most pronounced when aroma presentation coincides with swallowing, inducing retronasal aroma olfaction.

Differences in texture can also lead to differences in perceived aroma intensity. Visschers et al. (*6*) showed that the perceived intensity of aroma decreases with increasing firmness of the food that is consumed. The aroma and texture stimuli were presented separately, using an olfactometer. However, these cross-modal interactions did not depend on ortho- or retronasal aroma presentation and perception. In addition, the neural processing of aroma is influenced by the pathway for aroma perception. Small et al. (*2*) investigated response patterns to ortho- and retronasal olfaction at a central nervous level, by using functional magnetic resonance imaging (fMRI). They report that aroma perception is greater to a food aroma (chocolate) compared to a nonfood aroma (lavender). Its processing may be related to differential reward circuits for food, but not nonfood aromas (*8*). Orthonasal olfaction appears to correlate with the anticipatory phase in food reward, whereas retronasal olfaction is related to the consumption phase, receipt of a reward.

Engineering Retronasal Aroma Perception. The ability to administer aroma stimuli to subjects separately from other stimuli from the food matrix (associated with other ingredients, textures, and tastes) enables investigation of the relative importance of aroma stimuli for perception. Both atmospheric pressure chemical ionization−mass spectrometry (APcI-MS) and olfactometry have proven to be of great importance in measuring as well as mimicking aroma release. The release of aromas during food consumption can be measured and adjusted, using APcI-MS

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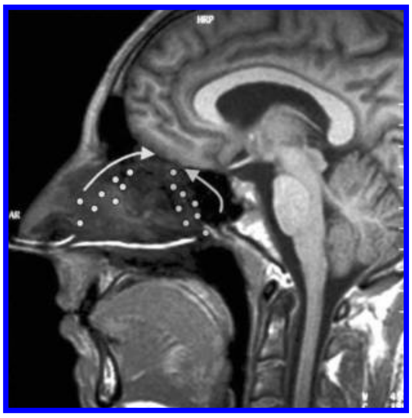

Figure 1. Magnetic resonance image (MRI) showing placement of the nasal cannulae at the external nares to achieve orthonasal delivery and at the retropharynx to achieve retronasal delivery. Dots and arrows depict the idealized distribution and flow direction of odorants delivered orthonasally (via the external nares) or retronasally (via the retropharynx) (*2*).

technology (*9*, *10*). On the other hand, tailored olfactometer equipment, originally developed for medical purposes, is finding more and more applications in aroma research (*6*, *7*, *11*). Olfactometry can be applied to deliver specific, well-defined aroma profiles consisting of a single aroma component or a mixture of multiple aroma components. As described by Visschers et al. (*6*), delivering food-related aroma stimuli to subjects via an olfactometer involves fine-tuning of many parameters, such as the initial concentration of the aroma component(s) in a suitable solution, volatility, and partitioning of the aroma component(s) from the solvent into the air flow, air dilution factor of the olfactometer, aroma pulse timing, and aroma pulse length. Delivery of aroma stimuli in a manner that reflects aroma release during food intake is complex. For retronasal aroma delivery, a tube of approximately 9 cm in length is cut from a sterile silicon suction catheter (*1*). The tube is placed inside the nose, such that the opening is in the epipharynx. For aroma stimulation the tube is connected to the outlet of the olfactometer. The olfactometer delivers aroma stimuli, which are embedded into a constant flow of odorless, humidified air of controlled temperature (total flow = 8 L/min, 60% relative humidity, 40 °C).

It has been demonstrated that the aroma profile that is generated with the olfactometer closely resembles the concentration of volatiles in the oronasal cavity measured in individuals during ingestion of a specific food product (*10*, *12*). The used approach is based on data from in vivo studies with real-time measurement of aroma release, using APcI-MS. This enables the design of complete aroma release profiles that mimic those obtained by in vivo measurement during food consumption (*6*) (**Figure 2**). The combination of mass spectrometry and olfactometry provides a unique and novel approach to investigate the role of aroma for perception.

AROMA AS A TRIGGER FOR SATIATION

During the consumption of a meal, aroma molecules reach the olfactory epithelium retronasally. Activation of brain areas by a retronasally sensed food odor is associated with the perception of food that is consumed and is hypothesized to contribute to satiation (*2*), that is, sensory-related satiation. The extent of sensory stimulation may therefore be related to meal termination (*13*, *14*).

It is hypothesized that differences in the extent of retronasal aroma release during consumption may be one of the reasons that people vary in their satiation characteristics, due to differences in perceived intensity, duration, or quality of retronasal aroma stimulation. Therefore, the effect of retronasal aroma release on satiation and food intake is studied from both the consumer and food product points of view. **Figure 3** gives an overview of some of the features that are suggested to contribute to the extent of retronasal aroma stimulation and subsequently sensory satiation, from both the consumer and food product points of view. Tailoring these features may lead to a higher quality and/or quantity of retronasal aroma stimulation, which in turn may lead to enhanced feelings of satiation and ultimately contribute to a decrease in food intake.

Uncontrolled Subject (Consumer)- and Food Product-Specific Features. The subject's extent of in vivo retronasal aroma release is an uncontrolled characteristic that is suggested to vary across individuals. First, the question was addressed whether subjects can be segmented on the basis of their extent of retronasal aroma release, using real-time APcI-MS, and whether this depends on the type of food product they consume (*15*). To this end, in vivo retronasal aroma release was assessed for food products, which varied in texture from (semi)liquid to solid. Ultimately, the aim was to determine whether subject differences in the extent of retronasal aroma release are linked to subject differences in sensory satiation and food intake behavior. A higher extent of retronasal aroma release may result in more sensory stimulation, which in turn may lead to increased feelings of satiation and decreased food intake. Retronasal aroma release intensity and profile morphology appeared to be subject specific, and relatively independent of the type of food product that subjects consumed. For instance, a subject who had a relatively high retronasal aroma release intensity for a (semi)liquid food product also appeared to have a relatively high retronasal aroma release intensity for a solid food product. This implies that the extent of retronasal aroma release is a physiological feature that characterizes any individual. Subject differences in oral processing parameters, such as salivary flow rate, nasal anatomy, bite size, and eating speed may be (partly) responsible for this finding (*16*−*20*).

Additionally, for all subjects it was noted that there are absolute differences between food products in the duration of retronasal aroma release comparing (semi)liquid and solid food products, because of differences in oral processing. Solid food products require considerable chewing and swallowing, due to their firmer texture. Consequently, most subjects had an immediate and prolonged retronasal aroma release. In contrast to the consumption of solid food products, most subjects had a short and spiked retronasal aroma release pattern during the consumption of (semi)liquid food products (*10*, *21*). Accordingly, food product differences in the extent of retronasal aroma release are explained by differences in food structure and composition and the oral processing that is evoked (*22*−*25*).

The demonstrated subject and product differences with respect to the extent of retronasal aroma release may be one of the reasons that people vary in their satiation characteristics and may have implications for the regulation of food intake. A higher extent of retronasal aroma release may therefore result in more sensory stimulation, which in turn may contribute to increased feelings of satiation and decreased food intake (*2*, *13*, *14*). This may be one of the explanations why (soft) solid foods appear to be more satiating than liquid foods (*26*−*30*).

Moreover, for a subset of the subjects ad libitum food intake was measured. Interestingly, a negative trend was observed between the extent of retronasal aroma release and the amount of ad libitum food intake. Subjects who had a higher extent of retronasal aroma release tended to consume less. This finding may support the hypothesis that subject differences in the extent of retronasal aroma release are linked to subject differences in

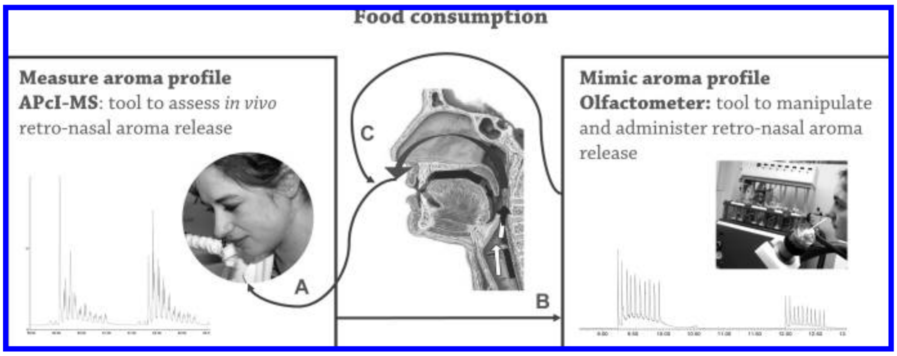

Figure 2. Illustration of the used approach to deliver specific, well-defined aroma profiles that mimic those obtained during food consumption. The release of aromas during food consumption is measured using APcI-MS technology (**A**). Using a computer-controlled stimulator based on air dilution olfactometry, complete aroma release profiles are designed that mimic those obtained by applying APcI-MS technology (**B**). Specific, well-defined aroma profiles are retronasally delivered to the subject, combined with the taste and mouthfeel sensation of the nonaromatized food product in the mouth (**C**).

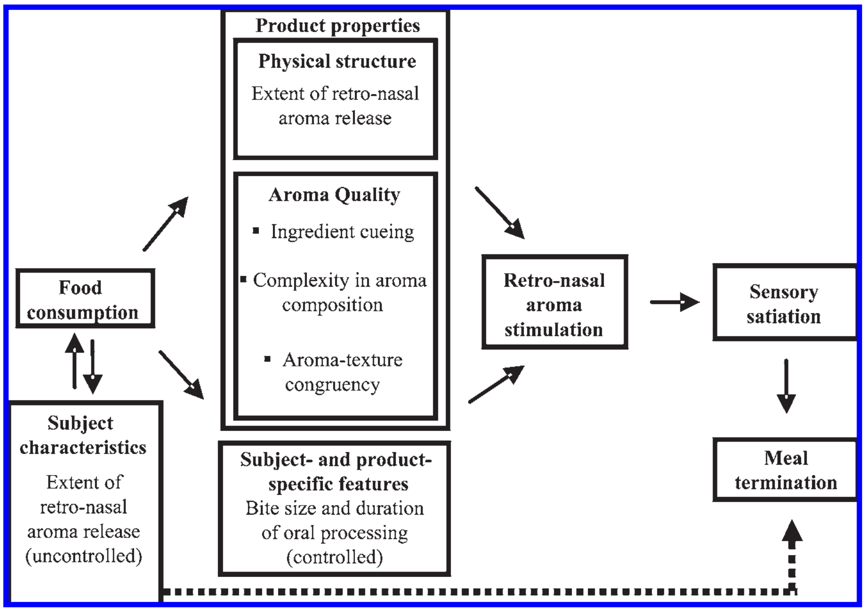

Figure 3. Schematic representation of features that are suggested to contribute to the extent of retronasal aroma stimulation and sensory satiation, from both consumer and food product points of view.

sensory satiation and food intake behavior. To our knowledge, this observation has not been reported before. A follow-up study with a larger subject population, which is more segmented with respect to BMI, is needed to ultimately quantify an immediate, significant effect of a contribution of the extent of retronasal aroma release to food intake behaviors.

Physical Structure of a Food Product. Obviously, the level of aroma stimulation depends on the duration of release of the aromas and thereby differs for different food structures and compositions. After all, the physical structure of a food product that is consumed is important for the extent of retronasal aroma release during consumption. It is hypothesized that relative prolonged retronasal aroma release, as observed in solid foods, is an important factor in generating an enhanced level of satiation compared to the level resulting from consuming a (isoenergetic and isovolumetric) beverage. In an olfactometer-aided experimental design to deliver aroma stimuli separately from taste and mouth feel, it was studied whether a beverage becomes more satiating when the retronasal aroma release profile coincides with the profile of a (soft) solid food (*31*). Results showed that a beverage with an aroma release profile similar to a (soft) solid food is able to increase the subject's feeling of satiation significantly. To our knowledge, this is the first time that such a result has been observed. Altering the duration of retronasal aroma release appears to have the potential to increase perceived satiation.

Aroma Quality. Apart from the physical structure of a food product and the extent of retronasal aroma release that is evoked, aroma quality is a product property that may affect retronasal aroma stimulation. This in turn may contribute to enhanced feelings of satiation and a decrease in food intake. To this end, the effect of ingredient-related aroma cues, complexity in aroma composition, and congruency in aroma and texture on satiation and food intake was investigated (*32*, *40*, *46*).

Ingredient-Related Aroma Cues. To a large extent, satiation and satiety are conditioned (learned) responses. Sensory signals are mostly unconsciously learned to be associated with the metabolic consequences of food products. It was studied whether specific aroma stimuli, which subjects do not consciously recognize, are able to cue for satiation (*32*). Three sensory cueing stimuli were tested, which are conceived to be related to fat content (i.e., lactones), carbohydrate content (i.e., maltol), and the breakdown of protein content (i.e., "animalic"). Custard products with the addition of maltol or animalic at sensory detection threshold were able to increase subjects' feeling of fullness significantly. This result is in line with our expectations, because it is hypothesized that animalic cues for incongruence between the actual flavor and the flavor expectation attributable to the consumed food product, consequently unconsciously triggering satiation (i.e., perceived fullness). Alternatively, the response to the cueing aroma stimuli might be a learned response, that is, conditioned satiation, possibly due to flavor-nutrient learning (cf. refs *33−35*). Subjects may associate the aroma stimuli animalic and maltol as cueing for the energy content (i.e., postingestive consequences) of protein and carbohydrate, respectively. Moreover, our results are in line with observations that macronutrients have different satiating efficiencies, in which protein is more satiating, followed by carbohydrate and fat as least satiating (*36−39*). Accordingly, specific cueing aroma stimuli at the sensory detection threshold are able to contribute to perceived fullness. From this study, it can, however, not be concluded whether this is due to incongruence between the actual flavor and the flavor expectation attributable to the consumed food product or due to perceiving the aroma stimuli cueing for the energy content of specific macronutrients.

Complexity in Aroma Composition. In addition, the acute effect of complexity in aroma composition on satiation and food intake was investigated in either an olfactometer-aided or an ad libitum eating experimental design (*40*). Apart from the differences in timing of the appetite-regulating effects, both experimental settings demonstrated that a multicomponent strawberry aroma, which is perceived as being more complex, yet of similar aroma quality, intensity, and pleasantness compared to a single-component strawberry aroma, is able to enhance satiation. This observation is in line with our expectations. Assuming that the total amount of exposure to a food's sensory properties determines the total decline in desire to eat, it is hypothesized that increased sensory stimulation from a more complex aroma further reduces the desire to eat and enhances satiation. This is probably caused by concurrent exposure to multiple aroma components cueing for sensorily similar strawberry perception. To our knowledge, this result has not been described before. Food products that are perceived as being more complex are usually reported to delay the development of sensory satiation (*41−43*). However, in those observations perceived complexity may implicitly cue for variation, leading to increased meal size (*44*,*45*). In the present study, perceived complexity did not result in consciously perceived sensory differences between the two different strawberry-aromatized yogurt products. In addition, the results of this study show that the methodology of the olfactometer-aided aroma stimulation proves to be representative of a real-life setting with regard to aroma exposure and satiation.

Aroma−Texture Congruency. Comparable to the hypothesis for the concept about aroma complexity, increased sensory stimulation from a food product congruent in aroma and texture is expected to further reduce the desire to eat. Also here, this is probably caused by concurrent sensory exposure to multiple sensory modalities cueing for similar sensory perception (i.e., creaminess) (*46*). Satiation-enhancing effects regarding aroma−texture congruency were tested with creamy custard, either vanilla-aromatized (i.e., congruent with creamy texture) or lemon-aromatized (i.e., incongruent with creamy texture), served in a preload ad libitum experimental setting. It is hypothesized that satiation and food intake are affected by the level of congruency as well as by variation of successive exposure to aroma−texture combinations. The results showed that subjects feel significantly more satiated when preload and ad libitum intakes share the identical aroma compared to varied aromas. This may point to a "seeking for variety" principle (*47*). No satiation-enhancing effects of congruency were observed. However, a follow-up study with ad libitum intake only, that is, not preceded by a preload, could be more appropriate to determine the effect of aroma−texture congruency on meal termination.

Controlled Subject- and Food Product-Specific Features. In addition to (uncontrolled) subject and product features, the effect of bite size and duration of oral processing on the extent of retronasal aroma release was investigated (*48*). Subjects consumed dark chocolate-flavored custard while they were exposed to both free or fixed bite size (5 and 15 g) and duration of oral processing before swallowing (3 and 9 s) in a crossover design. It is hypothesized that consuming food either in multiple small bite sizes or with a longer duration of oral processing evokes more oral processing per gram consumed and increases transit time in the oral cavity. As expected, small bite sizes contributed significantly to a higher cumulative extent of retronasal aroma release per gram, whereas a longer duration of oral processing tended to result in more retronasal aroma release during consumption of a fixed amount of dark chocolate-flavored custard. However, the effect of oral processing time may be significant with a more solid food product. As reported by Zijlstra et al. (*49*,*50*), consumption in small bite sizes or with a longer duration of oral processing results in a lower ad libitum food intake. The results of the present study provide an additional, possibly complementary, explanation for the ad libitum intake results obtained by Zijlstra et al. (*49*, *50*) from a retronasal aroma release perspective, stimulating olfactory receptors. Differences in the extent of retronasal aroma release may thus contribute to the decrease in food intake in certain eating conditions.

Efficacy of the Different Aroma Concepts. The aforementioned studies support the observation that retronasal aroma release is able to induce satiation. Although the extent of retronasal aroma release appears to be subject specific, food product properties can be tailored in such a way that these can lead to a higher quality and/or quantity of retronasal aroma stimulation, which in turn provokes enhanced feelings of satiation and ultimately may contribute to a decrease in food intake.

Among the proof-of-principle studies that were performed, the prolongation of the duration of retronasal aroma release, the addition of specific ingredient-related aroma cues, the engineering of more complex aroma compositions, and the adaptation of bite size or duration of oral processing proved to be valuable aroma concepts for inducing satiation. The change in perceived satiation between the test product and placebo product varied for the different aroma concepts between 6 and 12 mm on a 100 mm visual analogue scale (VAS). This corresponds to an increase in perceived satiation of, respectively, 384% during stimulation with a prolonged retronasal aroma release, 38% during consumption of custard with addition of maltol, 42% during stimulation with a more complex aroma, 41% after consumption of custard with the addition of animalic, and 22% after consumption of yogurt with a more complex aroma. Apart from aroma−texture congruency, all aroma concepts reveal efficacy with regard to perception.

Despite significant changes in subjective experience, no impact on ad libitum amount consumed was observed for the different aroma concepts. This dissociation is a common observation in the field and similar to previous studies (*29*,*52−54*). As discussed by Veldhorst et al. (*55*), it is likely that the magnitude of the present effect in perceived satiation is too small to have an effect on the amount consumed ad libitum. Veldhorst et al. (*55*) showed that differences in appetite ratings in a preload−ad libitum meal design need to be at least > 35−40% to have a significant effect of 17−20% on subsequent energy intake. In a follow-up study, it would be a great challenge to obtain also a significant effect on actual food intake. An experimental design aiming at ad libitum consumption only is probably the most appropriate design to demonstrate aroma-induced satiation and, ultimately, accelerated meal termination (*56*).

Engineering Food Products That Lead to Increased Retronasal Aroma Stimulation. The combination of mass spectrometry and olfactometry provides a unique and novel approach to investigate the role of aroma for satiation. APcI-MS technology proves again to be an appropriate tool to measure the effects of oral processing on retronasal aroma release during food consumption. In future measurements, APcI-MS technology may be applied as a noninvasive biomarker to measure food oral processing efficiency from a retronasal aroma release perspective. Additionally, the use of tailored olfactometer equipment has been shown to be of great importance in mimicking aroma release during food consumption. Explicitly, in the study on aroma complexity, the results of this study validate the methodology of the olfactometer-aided aroma stimulation as representative of a real-life setting with regard to aroma exposure and satiation. The olfactometer-aided approach proves to be an appropriate tool for "fast prototyping", meaning that it is not necessary to manufacture a complete food product with inclusion of a specific aroma concept before the relative importance of that aroma concept can be investigated in vivo.

Examples of Food Technology Applications. For prolongation of the duration of retronasal aroma release during food consumption, examples of applications could be the development of food products with an increase of aftertaste or an increased or lingering aroma release via flavor delivery systems or encapsulation technology or the development of long-chewable food structures in beverages that evoke substantially more oral processing and an increase in transit time in the oral cavity. Furthermore, a reduction in bite size by tailored packaging may support the "right" oral processing behavior in food products.

Other applications could be the addition of specific ingredient-related aromas at sensory detection threshold to food products, that is, aromas cueing for the energy content of protein, or the engineering of multicomponent aroma compositions, which provide more "body/gestalt" to food products.

ROLE OF AROMA IN THE ORIGIN OF OBESITY

The human body exerts a strong defense against under-nutrition and weight loss, but applies a much weaker resistance to overconsumption and weight gain. This means that weight gain by overconsumption may occur despite efforts to prevent it (*51*). Overeating is an important aspect in the complex and multifaceted origin of obesity (*57*). Originally, overeating served to anticipate food insecurity. A number of ethnicities still possess this survival mechanism. In this context, for example, the off-reserve aboriginal population is reported to have a high prevalence of overweight and obesity (*58−60*). Subjects may differ in their ability to apply or reduce the capacity to overeat. The extent of retronasal aroma release is suggested to play a regulating role herein.

The present studies demonstrate that retronasal aroma release is able to contribute to satiation induction and possibly to meal termination. This finding supports the hypothesis that efficient retronasal aroma release, which is a subject-specific feature, is able to reduce the capacity to overeat by triggering satiation.

In previous studies, in which, for example, the effect of a specific food ingredient on satiety was investigated (*61,62*), retronasal aroma release concurrently contributed to satiation. Because retronasal aroma stimulation was not the primary focus in these studies, aroma-induced satiation has not been described before. However, in principle, this effect should always be taken into account during food consumption, irrespective of the type of food product consumed.

Differences in the extent of retronasal aroma release during consumption may be one of the reasons that people vary in their satiation characteristics, which may prevent them from overeating or not. Possibly, normal weight and obese subjects differ in the regulation of this food intake mechanism. In contrast to normal weight subjects, obese subjects could evoke limited extent of retronasal aroma release during food consumption. This may result in less sensory stimulation, which in turn may lead to decreased feelings of satiation and increased food intake. To test this assumption, it is desired to design a study in which normal weight subjects and overweight/obese subjects are exposed to an "all you can eat" buffet. It is hypothesized that overweight/obese subjects are capable of overeating. In a follow-up study, physiological differences during food consumption may be observed between normal weight and obese subjects, for example, differences in oral processing or retronasal aroma delivery to the olfactory epithelium. The rewarding function of food for obese subjects may be limited compared to normal weight subjects (cf. ref *63*). It would be interesting to determine whether the in vivo retronasal aroma release, by using APcI-MS technology, matches the subjective aroma perception by performing time−intensity measurements during food consumption.

Interestingly, in the present study (*15*), a negative trend is observed between the extent of retronasal aroma release and the amount of ad libitum food intake. However, a relationship between the extent of retronasal aroma release and BMI is not shown. A larger follow-up study with a group of normal weight subjects versus a group of overweight/obese subjects is needed to confirm a possible effect of the extent of retronasal aroma release on food intake, energy intake, and BMI.

DISCUSSION

The extent of retronasal aroma release appears to be a physiological feature that characterizes any individual. Although the extent of retronasal aroma release appears to be subject specific, food product properties can be tailored in such a way that these can lead to a higher quality and/or quantity of retronasal aroma stimulation. This in turn provokes enhanced feelings of satiation and ultimately may contribute to a decrease in food intake.

The application of aroma in food product development for inducing satiation is promising and appealing. Complementary to ingredients that focus on the postingestive and postabsorptive stage of the satiety cascade, retronasal aroma release, operating during food ingestion, has a consumer benefit that is immediately noticeable.

The current state-of-the-art in this field of research is still preliminary. The explorative research, as described in this paper, shows that the efficacy of the different aroma concepts for inducing satiation may be relatively small. Besides, no impact on ad libitum amount consumed is observed.

Among the proof-of-principle studies that were performed, the prolongation of the duration of retronasal aroma release, the addition of specific ingredient-related aroma cues, the engineering of more complex aroma compositions, and the adaptation of bite size or duration of oral processing may prove to be valuable aroma concepts for the development of foods containing triggers that induce or increase the feeling of satiation. The next challenge is to implement these concepts into real food products.

ACKNOWLEDGMENT

This paper is adapted from R.M.A.J.R.'s "Retro-nasal aroma release and satiation", Ph.D. thesis, 2009, ISBN 978-90-9024360-3.

LITERATURE CITED

(1) Negoias, S.; Visschers, R.; Boelrijk, A.; Hummel, T. New ways to understand aroma perception. *Food Chem.* **2008**, *108*, 1247–1254.

(2) Small, D. M.; Gerber, J. C.; Mak, Y. E.; Hummel, T. Differential neural responses evoked by orthonasal versus retro-nasal odorant perception in humans. *Neuron* **2005**, *47*, 593–605.

(3) Mozell, M. M. Evidence for a chromatographic model of olfaction. *J. Gen. Phys.* **1970**, *56*, 46–63.

(4) Kent, P. F.; Mozell, M. M.; Youngentob, S. L.; Yurco, P. Mucosal activity patterns as a basis for olfactory discrimination: comparing behavior and optical recordings. *Brain Res.* **2003**, *981*, 1–11.

(5) Burdach, K. J.; Kroeze, J. H.; Koster, E. P. Nasal, retronasal, and gustatory perception: An experimental comparison. *Percept. Psychophys.* **1984**, *36*, 205–208.

(6) Visschers, R. W.; Jacobs, M. A.; Frasnelli, J.; Hummel, T.; Burgering, M.; Boelrijk, A. E. M. Cross-modality of texture and aroma perception is independent of orthonasal or retro-nasal stimulation. *J. Agric. Food Chem.* **2006**, *54*, 5509–5515.

(7) Bult, J. H. F.; de Wijk, R. A.; Hummel, T. Investigations on multimodal sensory integration: texture, taste, and ortho- and retronasal olfactory stimuli in concert. *Neurosci. Lett.* **2007**, *411*, 6–10.

(8) Berridge, K. C. Food reward: brain substrates of wanting and liking. *Neurosci. Biobehav. Rev.* **1996**, *20*, 1–25.

(9) Taylor, A. J.; Linforth, R. S. T.; Harvey, B. A.; Blake, A. Atmospheric pressure chemical ionisation mass spectrometry for *in vivo* analysis of volatile flavour release. *Food Chem.* **2000**, *71*, 327–338.

(10) Weel, K. G. C.; Boelrijk, A. E. M.; Burger, J. J.; Gruppen, H.; Voragen, A. G. J.; Smit, G. A protocol for measurement of in vivo aroma release from beverages. *J. Food Sci.* **2003**, *68*, 1123–1128.

(11) Heilmann, S.; Hummel, T. A new method for comparing orthonasal and retronasal olfaction. *Behav. Neurosci.* **2004**, *118*, 412–419.

(12) de Kok, P. M. T.; Boelrijk, A. E. M.; de Jong, C.; Burgering, M. J. M.; Jacobs, M. A. MS-nose flavour release profile mimic using an olfactometer. In *Developments in Food Science; Flavour Science, Recent Advances and Trends*; Bredie, W., Petersen, M. A., Eds.; Elsevier: London, U.K., 2006; Vol. *43*, pp 585−599.

(13) Hetherington, M.; Rolls, B. J.; Burley, V. J. The time course of sensory-specific satiety. *Appetite* **1989**, *12*, 57–68.

(14) Hetherington, M. M.; Boyland, E. Short-term effects of chewing gum on snack intake and appetite. *Appetite* **2007**, *48*, 397–401.

(15) Ruijschop, R. M. A. J.; Burgering, M. J. M.; Jacobs, M. A.; Boelrijk, A. E. M. Retro-nasal aroma release depends on both subject and product differences: a link to food intake regulation? *Chem. Senses* **2009**, *34*, 395–403.

(16) Brown, W. E.; Dauchel, C.; Wakeling, I. Influence of chewing efficiency on texture and flavour perceptions of food. *J. Texture Stud.* **1996**, *27*, 433–450.

(17) Buettner, A.; Beer, A.; Hanning, C.; Settles, M. Observation of the swallowing process by application of videofluoroscopy and real-time magnetic resonance imaging-consequences for retro-nasal aroma stimulation. *Chem. Senses* **2001**, *26*, 1211–1219.

(18) Buettner, A.; Beer, A.; Hanning, C.; Settles, M.; Schieberle, P. Physiological and analytical studies on flavor perception dynamics as induced by eating and swallowing process. *Food Qual. Pref.* **2002**, *13*, 497–504.

(19) Wright, K. M.; Sprunt, J.; Smith, A. C.; Hills, B. P. Modeling flavor release from a chewed bolus in the mouth. Part 1. Mastication. *Int. J. Food Sci. Technol.* **2003**, *38*, 351–360.

(20) Pionnier, E.; Chabanet, C.; Mioche, L.; Le Quere, J. L.; Salles, C. I. In vivo aroma release during eating of a model cheese: relationships with oral parameters. *J. Agric. Food Chem.* **2004**, *52*, 557–564.

(21) Brauss, M. S.; Balders, B.; Linforth, R. S. T.; Avison, S.; Taylor, A. J. Fat content, baking time, hydration and temperature affect flavour release from biscuits in model-mouth and real systems. *Flavour Fragrance J.* **1999**, *14*, 351–357.

(22) Linforth, R. S. T.; Baek, I.; Taylor, A. J. Simultaneous instrumental and sensory analysis of volatile release from gelatine and pectin/gelatine gels. *Food Chem.* **1999**, *65*, 77–83.

(23) Cook, D. J.; Linforth, R. S. T.; Taylor, A. Effects on hydrocolloid thickeners on the perception of savory flavors. *J. Agric. Food Chem.* **2003**, *51*, 3067–3072.

(24) Lethuaut, L.; Weel, K. G.; Boelrijk, A. E.; Brossard, C. D. Flavor perception and aroma release from model dairy desserts. *J. Agric. Food Chem.* **2004**, *52*, 3478–3485.

(25) van Ruth, S. M.; de Witte, L.; Uriarte, A. R. Volatile flavor analysis and sensory evaluation of custard desserts varying in type and concentration of carboxymethyl cellulose. *J. Agric. Food Chem.* **2004**, *52*, 8105–8110.

(26) Haber, G. B.; Heaton, K. W.; Murphy, D.; Burroughs, L. F. Depletion and disruption of dietary fibre. Effects on satiety, plasma-glucose, and serum-insulin. *Lancet* **1977**, *2*, 679–682.

(27) Mattes, R. D.; Rothacker, D. Beverage viscosity is inversely related to postprandial hunger in humans. *Physiol. Behav.* **2001**, *74*, 551–557.

(28) Mattes, R. Soup and satiety. *Physiol. Behav.* **2005**, *83*, 739–747.

(29) Tsuchiya, A.; Almiron-Roig, E.; Lluch, A.; Guyonnet, D.; Drewnowski, A. Higher satiety ratings following yoghurt consumption relative to fruit drink or dairy fruit drink. *J. Am. Diet. Assoc.* **2006**, *106*, 550–557.

(30) Zijlstra, N.; Mars, M.; de Wijk, R. A.; Westerterp-Plantenga, M. S.; de Graaf, C. The effect of viscosity on ad libitum food intake. *Int. J. Obes.* **2008**, *32*, 676–683.

(31) Ruijschop, R. M. A. J.; Boelrijk, A. E. M.; de Ru, J. A.; de Graaf, C.; Westerterp-Plantenga, M. S. Effects of retro-nasal aroma release on satiation. *Br. J. Nutr.* **2008**, *99*, 1140–1148.

(32) Ruijschop, R. M. A. J.; Boelrijk, A. E. M.; Burgering, M. J. M.; de Graaf, C.; Westerterp-Plantenga, M. S. Effects of ingredient-related aroma cues on satiation and food intake. *Food Qual. Pref.* **2009**, submitted for publication.

(33) Booth, D. A.; Lee, M.; McAleavey, C. Acquired sensory control of satiation in man. *Br. J. Psychol.* **1976**, *67*, 137–147.

(34) Gibson, E. L.; Brunstrom, J. M. Learned influences on appetite, food choice and intake: evidence in human beings. In *Progress in Brain Research: Appetite and Body Weight—Integrative Systems and the Development of Anti-Obesity Drugs*; Cooper, S. J., Kirkham, T. C., Eds.; Elsevier: London, U.K., 2007; pp 271−300.

(35) Mobini, S.; Chambers, L. C.; Yeomans, M. R. Effects of hunger state on flavour pleasantness conditioning at home: flavour-nutrient learning vs. flavour-flavour learning. *Appetite* **2007**, *48*, 20–28.

(36) De Castro, J. M. Macronutrient relationships with meal patterns and mood in the spontaneous feeding behavior of humans. *Physiol. Behav.* **1987**, *39*, 561–569.

(37) De Graaf, C.; Hulshof, T.; Weststrate, J. A.; Jas, P. Short-term effects of different amounts of protein, fats, and carbohydrates on satiety. *Am. J. Clin. Nutr.* **1992**, *55*, 33–38.

(38) Stubbs, R. J. Macronutrient effects on appetite. *Int. J. Obes.* **1995**, *19*, S11–S19.

(39) Westerterp-Plantenga, M. S.; Pasman, W. J.; Yedema, M. J. W.; Wijckmans-Duijsens, N. E. G. Energy intake adaptation of food intake to extreme energy densities of food by obese and non-obese women. *Eur. J. Clin. Nutr.* **1996**, *50*, 401–407.

(40) Ruijschop, R. M. A. J.; Boelrijk, A. E. M.; Burgering, M. J. M.; de Graaf, C.; Westerterp-Plantenga, M. S. Acute effects of complexity in aroma composition on satiation and food intake. *Chem. Senses* **2009**, submitted for publication.

(41) Johnson, J.; Vickers, Z. Factors influencing sensory-specific satiety. *Appetite* **1992**, *19*, 15–31.

(42) Lévy, C. M.; MacRae, A.; Köster, E. P. Perceived stimulus complexity and food preference development. *Acta Psychol.* **2006**, *123*, 394–413.

(43) Weijzen, P. L. G.; Zandstra, E. H.; Alfieri, C.; de Graaf, C. Effects of complexity and intensity on sensory-specific satiety and food acceptance after repeated consumption. *Food Qual. Pref.* **2008**, *19*, 349–359.

(44) Hetherington, M. M.; Foster, R.; Newman, T.; Anderson, A. S.; Norton, G. Understanding variety: tasting different foods delays satiation. *Physiol. Behav.* **2006**, *87*, 263–271.

(45) Romer, M.; Lehrner, J.; van Wymelbeke, V.; Jiang, T.; Deecke, L.; Brondel, L. Does modification of olfacto-gustatory stimulation diminish sensory-specific satiety in humans? *Physiol. Behav.* **2006**, *87*, 469–477.

(46) Harthoorn, L. F.; Ruijschop, R. M. A. J.; Weinbreck, F.; Burgering, M. J.; De Wijk, R. A.; Ponne, C. T.; Bult, J. H. F. Effects of aroma-texture congruency within dairy custard on satiation and food intake. *Food Qual. Pref.* **2008**, *19*, 644–650.

(47) Rolls, B. J.; Rowe, E. A.; Rolls, E. T.; Kingston, B.; Megson, A.; Gunary, R. Variety in meal enhances food intake in man. *Physiol. Behav.* **1981**, *26*, 215–221.

(48) Ruijschop, R. M. A. J.; Zijlstra, N.; Boelrijk, A. E. M.; Dijkstra, A.; Burgering, M. J. M.; de Graaf, C.; Westerterp-Plantenga, M. S. Effects of bite size and duration of oral processing on retro-nasal aroma release—features contributing to meal termination. *Physiol. Behav.* **2009**, submitted for publication.

(49) Zijlstra, N.; Mars, M.; Stafleu, A.; de Wijk, R. A.; Prinz, J. F.; Hück, N. L.; de Graaf, C. Effect of bite size and oral processing time of food on satiation. BFDG Abstracts. *Appetite* **2008**, *51*, 753.

(50) Zijlstra, N.; de Wijk, R. A.; Mars, M.; Stafleu, A.; de Graaf, C. Effect of bite size and oral processing time of a semi-solid food on satiation. *Am. J. Clin. Nutr.* **2009**, *90*, 269–275.

(51) Blundell, J. E.; King, N. A. Overconsumption as a cause of weight gain: behavioural-physiological interactions in the control of food intake (appetite). In *The Origins and Consequences of Obesity*; James, P., Bouchard, C., Bray, G., Eds.; Wiley: Chichester, U.K., 1996; pp 138−158.

(52) Mattes, R. Hunger ratings are not a valid proxy measure of reported food intake in humans. *Appetite* **1990**, *15*, 103–113.

(53) De Graaf, C.; Blom, W. A. M.; Smeets, P. A. M.; Stafleu, A.; Hendriks, H. F. J. Biomarkers of satiation and satiety. *Am. J. Clin. Nutr.* **2004**, *79*, 946–961.

(54) Harper, A.; James, A.; Flint, A.; Astrup, A. Increased satiety after intake of a chocolate milk drink compared with a carbonated beverage, but no difference in subsequent ad libitum lunch intake. *Br. J. Nutr.* **2007**, *97*, 579–583.

(55) Veldhorst, M. A. B.; Nieuwenhuizen, A. G.; Hochstenbach-Waelen, A.; Westerterp, K. R.; Engelen, M. P. K. J.; Brummer, R. J. M.; Deutz, N. E. P.; Westerterp-Plantenga, M. S. Comparison of the effects of a high- and normal-casein breakfast on satiety, 'satiety' hormones, plasma amino acids and subsequent energy intake. *Br. J. Nutr.* **2009**, *101*, 295–303.

(56) Ramaekers, M. G.; Luning, P. A.; Ruijschop, R. M. A. J.; van Boekel, M. A. J. S. Effect of aroma release profiles on *ad libitum* food intake. ECRO Abstracts. *Chem. Senses* **2009**, *34*, E20.

(57) Hill, J. O. Understanding and addressing the epidemic of obesity: an energy balance perspective. *Endocr. Rev.* **2006**, *27*, 750–761.

(58) Tremblay, M. S.; Pérez, C. E.; Ardern, C. I.; Bryan, S. N.; Katzmarzyk, P. T. Obesity, overweight and ethnicity. *Health Rep.* **2005**, *16*, 23–34.

(59) Yu, B. N.; Fieldhouse, P.; Hammond, G.; Sevenhuysen, G. Differential association of food insecurity and obesity in children and youth: a Canadian population-based study. NAASO Annual Scientific Meeting abstracts. *Obesity* **2006**, *14*, 180−182

(60) Garriguet, D. Obesity and the eating habits of the Aboriginal population. *Health Rep.* **2008**, *19*, 21–35.

(61) Diepvens, K.; Soenen, S.; Steijns, J.; Arnold, M.; Westerterp-Plantenga, M. S. Long-term effects of consumption of a novel fat emulsion in relation to body-weight management. *Int. J. Obes.* **2007**, *31*, 942–949.

(62) Hughes, G. M.; Boyland, E. J.; Williams, N. J.; Mennen, L.; Scott, C.; Kirkham, T. C.; Harrold, J. A.; Keizer, K. G.; Halford, J. C. The effect of Korean pine nut oil (PinnoThin) on food intake, feeding behaviour and appetite: a double-blind placebo-controlled trial. *Lipids Health Dis.* **2008**, *7*, 6.

(63) Volkow, N. D.; Wang, G. J.; Telang, F.; Fowler, J. S.; Thanos, P. K.; Logan, J.; Alexoff, D.; Ding, Y. S.; Wong, C.; Ma, Y.; Pradhan, K. Low dopamine striatal D2 receptors are associated with prefrontal metabolism in obese subjects: possible contributing factors. *Neuroimage* **2008**, *42*, 1537–1543.

Received for review April 30, 2009. Revised manuscript received August 6, 2009. Accepted September 10, 2009. This work was done within DiOGenes. DiOGenes is the acronym of the project "Diet, Obesity and Genes" supported by the European Community (Contract FOOD-CT-2005−513946). The parties of the project are listed on the Website of the project (http://www.diogenes-eu.org/). Special acknowledgment is made to the Dutch Dairy Organization for cofinancing this project.