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Cross-Modality of Texture and Aroma Perception Is Independent of Orthonasal or Retronasal Stimulation

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To assess the influence of orthonasal and retronasal stimulation on cross-modal interactions between texture and flavor perception of food, a series of experiments have been conducted. Healthy human subjects were exposed to strawberry aroma pulses delivered by a computer-controlled stimulator based on air dilution olfactometry. Just prior to exposure to the aroma, the human subjects consumed water, custard, or protein gels with different textures without any added aroma. The aroma was delivered as a sequence of aroma pulses, in either an orthonasal or a retronasal fashion. The retronasal presentation of aroma with concomitant presentation of texture is thought to more closely mimick the in vivo flavor release of semisolid food products as compared to orthonasal stimulation. The time between oral consumption of the food, including swallowing, and the exposure to the aroma varied between 0.5 and 6.5 s. The subjects rated the intensity of the strawberry aroma. It was observed that the intensity of aroma decreased with increasing firmness of the food that was consumed. Aroma pulses delivered 6.5 s after swallowing were perceived as being more intense as compared to aroma pulses delivered immediately after swallowing. In conjunction with late delivery, the effect cross-modal interactions apparently decreased. Significantly higher odor intensities were reported for the aroma stimuli supplied orthonasally in comparison to retronasal administration. The observed cross-modal effect of texture on aroma intensity was not significantly altered by the mode of aroma delivery, i.e., orthonasal or retronasal stimulus administration.

KEYWORDS: Odor; retronasal stimulation; olfactometry; texture perception; flavor perception

INTRODUCTION

Human perception of food flavor and texture during consumption is a complicated process in which taste, mouth feel, vision, olfaction, the trigeminal system, and even auditory signals contribute to the total appreciation of a food product (*1*, *2*). When food is processed in the mouth, it is subjected to changes in temperature, mechanical deformation, and effects caused by saliva such as dilution and enzymatic breakdown of certain food ingredients such as starch (*3*). Nonvolatile compounds that are responsible for the basic tastes diffuse into the saliva and subsequently reach the gustatory receptors. Furthermore, during oral processing and after swallowing, volatile aroma compounds are released from the food matrix into the air and are thus able to flow to the olfactory epithelium where they interact with olfactory receptors. While eating and perceiving food, the different senses interact in a nonlinear way. Cross-modal phenomena in which taste influences the perception of the aroma (and vice versa) of a food product have been described (*4*−*6*). These types of effects are most prominent for sweetness and congruent flavors such as strawberry and include both synergistic and antagonistic effects. Cross-modal interactions between texture and aroma have in particular been reported for semisolid gelled food systems such as yogurt (*7*−*13*).

We have previously reported a study (*15*) in which non-sweetened gels with different hardnesses and water-holding capacities were aromatized with either ethyl butanoate or diacetyl. The intensity perception of the aroma compounds was determined as a function of time (*16*), while the aroma release was measured simultaneously by atmospheric pressure chemical ionization−mass spectrometry (APCI-MS, also called MS-nose). The overall aroma release during consumption was found to be independent of gel hardness or water-holding capacity. However, significant changes in aroma intensity between the gels were perceived by the majority of the panelists. We proposed that cross-modal aroma−texture interactions could be responsible for the observed effect. Since then, similar results have been reported by others (*4*−*6*). However, proving the hypotheses for soft solid products has been troublesome since data analysis is complicated by slightly different chewing regimes for the different panelists and subsequently observed differences in

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morphology of the aroma release curves (*17*). Therefore, we have now studied cross-modal aroma−texture interactions in which the aroma and texture stimuli are delivered to the senses separately. With an olfactometer, the delivery of aroma in the nose can be controlled while different nonaromatized liquids or soft solid food products are consumed in the mouth by the subjects. We now report the results of experiments aimed at studying the effect of texture perception on aroma perception while delivering the aroma and texture stimuli separately. Furthermore, our setup also enabled us to study the effect of orthonasal vs retronasal delivery of aroma in relation to aroma−texture interactions.

MATERIALS AND METHODS

Three types of thickened or gelled food systems were used that did not contain any added flavors in addition to plain water. The thickened systems comprised a custard dessert and two types of cold-set whey protein gels differing in texture. The custard dessert was prepared according to the standard recipe of the European COST 921 action (http://www.cost921.uni-wuppertal.de) and contained skim milk powder, modified tapioca starch, and sugar. Briefly, skim milk powder (Royal Friesland Foods, The Netherlands) was dissolved to a concentration of 3.5% fat into water and stirred for 16−24 h at 4 °C. Subsequently, 4% starch (VA85T, Avebe, The Netherlands), 5% sucrose, and 0.01% carrageenan were added to the cold solution while stirring continuously; 300−500 mL of the solution was placed in a water thermostat at 97 °C for 30 min while stirring continuously. After this, the custard was cooled in the refrigerator and allowed to rest for at least 16 h. The two types of cold set protein gels were prepared according to the method previously described (*18*). Briefly, for the firm gel, a 9% whey protein isolate (Bipro, JE 153-9-420 Davisco Foods International Inc., Le Sueur, MN) solution was heated at 68.5 °C for 2 h. After the solution was cooled to room temperature, this sample was diluted three-fold to a final protein concentration of 3% prior to adding the acidifying agent glucono-δ-lacton (GDL). GDL was obtained from Sigma Chemical Co. (St. Louis, MO). For the weak gels, 3% protein solutions were heated at 68.5 °C for 2 h and used without further dilution. In this way, gels of matching protein concentration (3% w/v) with different firmness could be prepared. The force at fracture in a compression measurement for these two types of gels differs by a factor of 2 (25 vs 50 g). The two gels both were scoopable but produced different textures. The strong gel was more sticky and resisted melting in the mouth longer than the weak gel. Both gels produced a clean mouth feel, and no particulate structures were perceived after swallowing. A full sensory description of these types of gels is forthcoming (van den Berg et al.; manuscript in preparation). A more detailed description of their fracture and rheological properties was published previously (*18*−*20*). Aspartame was added (0.012% final concentration) to both gels prior to acidification. The amount of aspartame added (0.012%) was slightly lower than calculated on the basis of a relative sweetness factor of 180 as compared to sucrose (*21*). However, adding more aspartame leads to an unacceptable off-taste in the WPI gels.

The bottled water was bought in the local supermarket (Evian in 1 L glass bottles). The strawberry aroma used was the standard flavor of the COST 921 action (http://www.cost921.uni-wuppertal.de), designed and supplied by Givaudan (Geneva, Switzerland), which contained 15 components including ethyl butyrate (90 mg/g), methyl dihydrojasmonate (5 mg/g), methyl cinnamate (24 mg/g), vanillin (5 mg/g), ethyl hexanoate (20 mg/g), benzyl acetate (2 mg/g), γ-decalactone (20 mg/g), hexanal (1 mg/g), *cis*-3-hexenol (15 mg/g), β-ionone (1 mg/g), ethyl iso-pentanoate (10 mg/g), methyl anthranilate (1 mg/g), furaneol (5 mg/g), styrallyl acetate (1 mg/g), *cis*-3-hexenyl acetate (5 mg/g), and triacetin (795 mg/g) as a solvent. Prior to use in the olfactometer, the strawberry flavor was diluted 10 times in propylene glycol.

Aroma Delivery and Sensory Evaluation. Employees of NIZO food research volunteered as subjects and were not trained specifically for this experiment, although all of them had previous experience in sensory evaluations of food texture and flavor. In our experience, extensive training of subjects can reduce the magnitude of cross-modal effects. The participants were given no information about the aim of the experiments other than an instruction to rate the strawberry aroma intensity after the pulse sequence was completed. The aroma was administered by means of a computer-controlled four-channel olfactometer based on air dilution olfactometry (OM4, Burghart, Wedel, Germany). The subjects only scored the perceived intensity during the tests. We considered the risk of halo dumping effects small since we focused on the significant changes in intensity score as a function of texture and mode of flavor delivery. Because potential halo dumping effects would be distributed randomly over these factors, halo dumping effects were not likely to yield a significant contribution to these changes.

Delivering food-related aroma stimuli with an olfactometer to panelists involved a variety of parameters. These parameters included initial concentration of the aroma compound(s) in a suitable solution, volatility and partitioning of the aroma compound(s) from the solvent into the air flow, air dilution factor of the olfactometer, aroma pulse timing, or aroma pulse length. Matching the aroma stimuli to such a level that can be genuinely related to food was thus a complex process. In our experience, working with pure aroma chemicals or highly concentrated odor solutions can result in extreme stimuli that do not relate at all to the real food situation. Our approach was based on our knowledge of measuring flavor release in vivo in real time using the APCI-MS (*21*−*23*). To determine a suitable solvent and dilution factor for the odor solution, the airflow from the olfactometer was directly inserted into the APCI-MS. In practice, the Teflon tubing outlet of the olfactometer was directly attached to the APCI-MS inlet capillary. In this way, we matched the timing and intensity of the aroma pulses generated by the olfactometer with in vivo flavor release profiles of food products that were measured with the APCI-MS sampling the nose of a human subject. In **Figure 1**, we demonstrate that indeed the arome profile generated with the olfactometer closely resembles the concentration of volatiles in the nose space measured for an individual subject.

Maintaining a continuous constant air flow through the diluted odor solution resulted in substantial depletion. Therefore, we used an interrupted flow method that minimized the necessary air stream through the odor solution. This resulted in limited depletion of aroma from the solution in the olfactometer during experimentation and subsequently in robust reproducible delivery of stimuli. In **Figure 2**, aroma pulse sequences generated with constant flow and interrupted flow were compared showing that there was no on-set difference between the different methods. Moreover, it was clear that a programmed pulse width of 1000 ms was exactly monitored in the real time with the APCI-MS (using a dwell time of 0.09 s), as well as programmed interpulse delays. In this way, complete flavor release profiles were designed that mimicked those obtained by in vivo experiments during the consumption of authentic food products (with high and low fat contents) as measured by APCI-MS (*24*).

In the current experimental setup, the air flow out of the olfactometer was kept constant at 7.5 L/min. To be as close as possible to natural aroma release conditions during consumption, a complete aroma release curve was administered by the olfactometer instead of one single aroma pulse. A natural aroma release curve was designed based on previous APCI-MS data for aroma release during consumption of liquids and semisolids. The release curve consisted of five consecutive pulses, each lasting 0.2 s with interpulse intervals of 0.8 s. The aroma dilution flow ratios for the five pulses within the profile varied from 4:3.5 to 1:6.5. The profile was designed in such a way that the envelope of the aroma pulses mimicked the reflux of air that occurred shortly after swallowing. The concentration and shape of the strawberry aroma pulse profile delivered to the subjects were the same for all measurements. **Figure 1** shows a comparison of an in vivo release signal (consumption of water flavored with the strawberry aroma, at a recommended dosage at 0.6 g/L) and the designed aroma release curve. For retronasal odor delivery, a silicon tube of approximately 6 cm in length was placed into the lower meatus of the nasal cavity following nasal endoscopy. For orthonasal delivery, this tube was positioned approximately 1 cm inside the anterior portion of the nose. **Figure 3** demonstrates the positions of the tubing for both orthonasal and retronasal stimulation (reproduced with permission from ref *25*). No specific selection of left

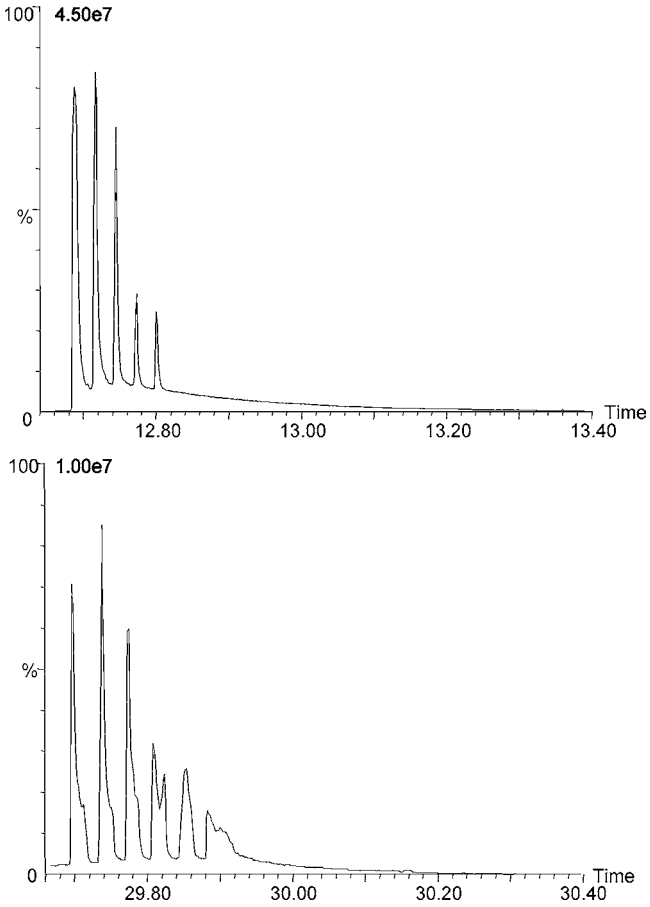

Figure 1. For the orthonasal and retronasal aroma delivery, both early and late, a single olfactometer-generated aroma profile was used. The aroma profile generated with the olfactometer consisted of five consecutive pulses with decreasing fractions of the total air flow being flavored (upper curve). The profile simulates the in vivo aroma release curve (lower curve). The lower curve is a single release profile of ethyl butyrate measured in vivo after swallowing that was measured for an individual subject.

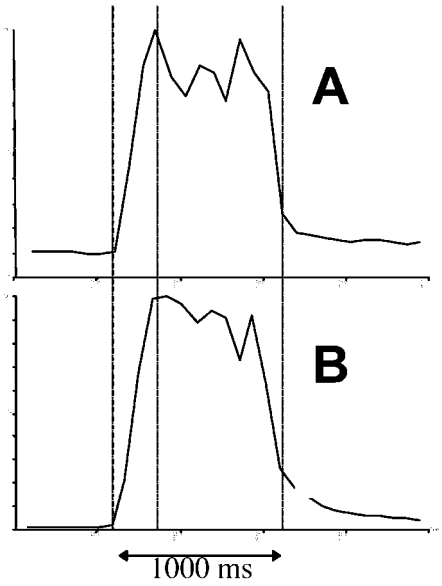

Figure 2. APCI-MS trace of ethyl butyrate delivered by the olfactometer with constant airflow (**A**) and with interrupted air flow (**B**) through the aroma solution.

or right nostrils was made. Introduction of the tubing to the nose was tolerated well by all subjects without causing major congestion or mucus

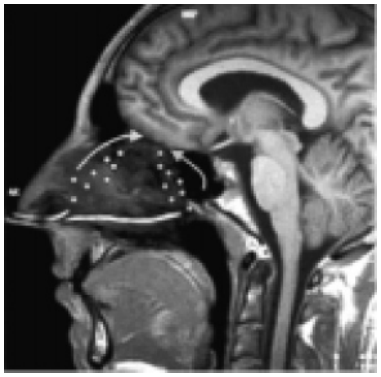

Figure 3. MRI image showing placement of the nasal cannulae at the external nares to achieve orthonasal delivery and at the retropharynx to achieve retronsasal delivery. Reprinted with permission from Small, D. M.; et al. *Neuron* **2005**, *47*, 593–605. Copyright 2005 Elsevier.

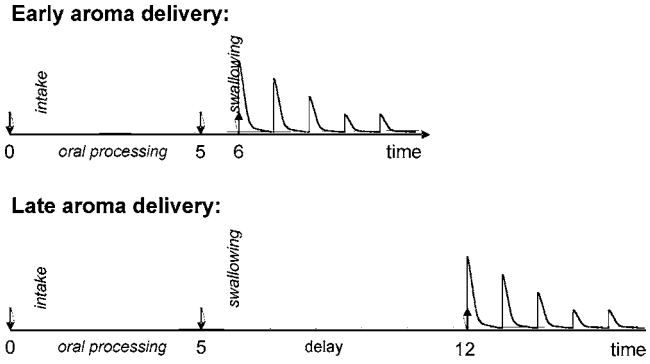

Figure 4. Figure illustrating the "early" (top) and "late" (bottom) aroma delivery sequence. Subjects were instructed to swallow the gels after 5 s of oral processing in both sequences.

discharge. The silicon tube was connected to the olfactometer while the panelist was sitting straight up in a chair, enabling concurrent consumption of gels and liquids. A specific protocol was established for the timing of aroma delivery. Subjects were instructed to swallow the gels after 5 s of oral processing. The aroma was delivered within either 1 s after the instruction for swallowing (early delivery) or after 6.5 s after the instruction for swallowing (late delivery; **Figure 4**). As a result of the followed protocol, the uncertainty in the timing was less than 1 s, independent of either orthonasal or retronasal delivery. No specific instruction with regard to breathing was given. Orthonasal and retronasal stimulation as well as early and late aroma delivery were randomized for every set of four food samples. All foods were served at room temperature. Gels were eaten with spoons, and water was sipped from a small straw. Subjects were asked to take a full spoon of custard or protein gel sample in their mouth. For the water sample, subjects were asked to take a quantity of water in their mouth, which was perceived as being a "normal" quantity to them. The intensity of the aroma profile was the same for all evaluations; however, the panelists were not aware of this fact.

Although the products were coded, it is likely that the subjects were able to identify the different samples from their visual appearance, since they did spoon or drink the samples themselves. Rating of strawberry aroma intensities was done within 20 s after administration of the aroma pulse on a visual analogue scale ranging from 0 to 10. Each subject rated a total of 64 samples comprising a four-fold duplicate set of ratings of four food samples with either orthonasal or retronasal stimulation as well as short or long delay. All factors were randomized. To prevent adaptation to the delivered aroma, the delay between the measurements amounted to a minimum of 30 s. A total of 11 adult subjects participated (five females). Statistical analysis of variance (ANOVA) was carried out using the two-way ANOVA module in the StatSoft Statistica software package. A Student, Newman, and Keuls full comparison test was also carried out to screen for significant differences between

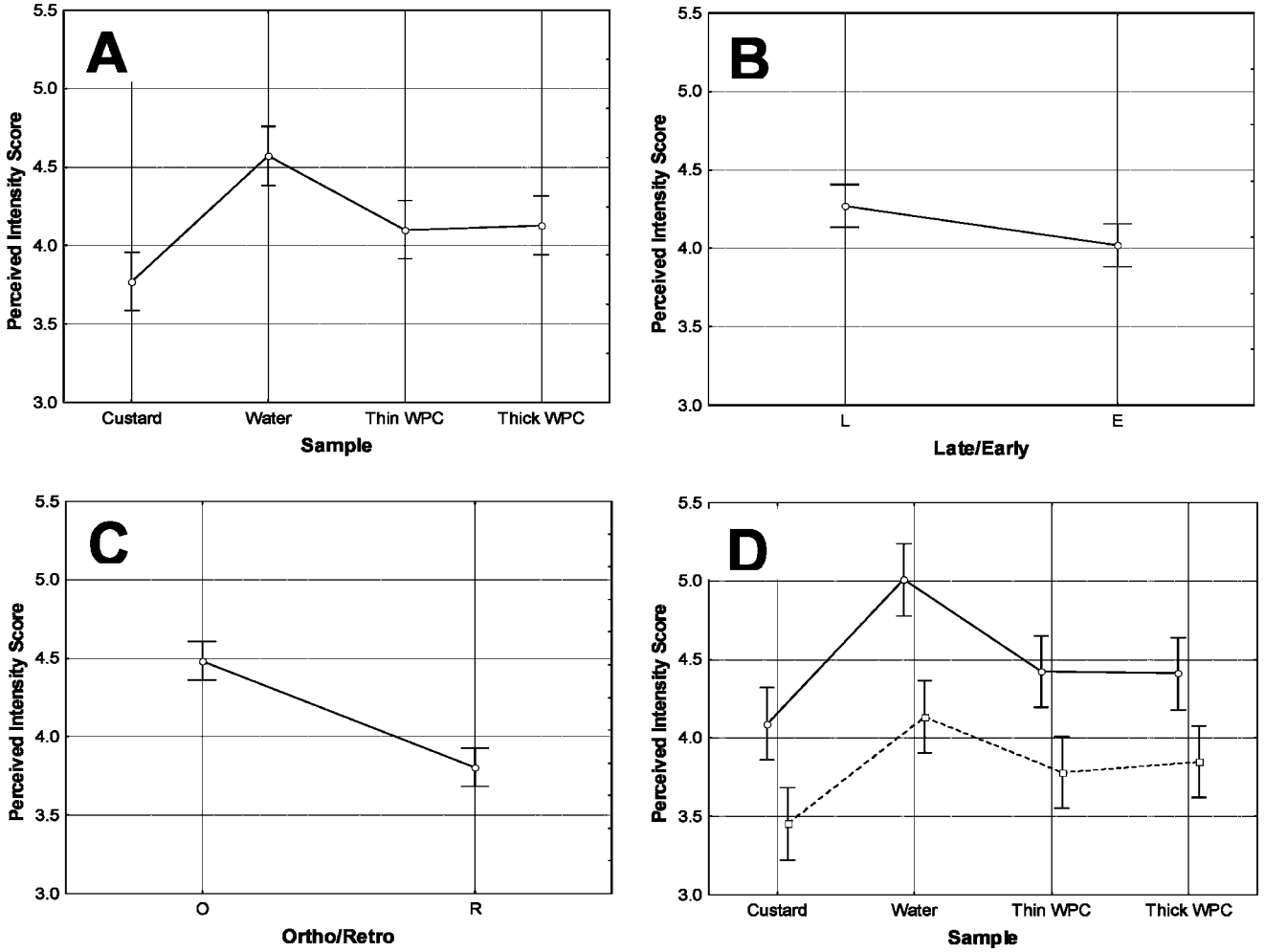

Figure 5. Average intensity ratings and graphical display of analysis of variance for (**A**) the results for the whole data set, averaging the scores of orthonasal and retronasal stimulation as well as the early and late administration of flavor ($F = 11.9$, $p < 0.00001$); (**B**) the results obtained separately for late and early stimulus presentation in relation to swallowing, averaging all samples and orthonasal and retronasal presentation ($F = 6.31$, $p = 0.012$); (**C**) the results obtained separately for orthonasal and retronasal stimulus presentation, averaging all samples and late and early presentation ($F = 59.44$, $p < 0.00001$); and (**D**) the results for the individual samples after splitting the data set up for orthonasal stimulus presentation (upper curve, $F = 10.23$, and $p < 0.00001$) and for retronasal stimulus presentation (lower curve, $F = 6.05$, and $p = 0.00051$). Vertical bars denote 95% confidence intervals.

individual instances of sample type, timing, and mode of delivery. We used further two-way ANOVA analysis to consider the interactions between the different factors investigated since these proved to be more powerful than the multiple comparison tests for this particular data set.

RESULTS

Cross-Modal Effects of Texture Perception on Aroma Perception. When the scores of orthonasal and retronasal stimulation as well as the early and late administration of flavor are first combined (**Figure 5A**), a significant effect of judges ($F = 52.1$, $p < 0.0001$) is observed, which implies that the individual judges were different in their intensity ratings and scaling of the aroma intensity. This is not surprising since no training sessions were included and all subjects rated the aroma intensity intuitively. We also observed a judge*sample effect, which was related to three out of the 11 judges and implies that their aroma perception was affected differently by the experimental factors from the other subjects. Although this increased the variance in our results, these ratings were included in the scores reported here. The average intensity of the strawberry aroma was different at the 95% confidence limit for the custard, water, and whey protein gels ($F = 18.9$, $p < 0.00001$). There was no significant difference between the two types of whey protein gels. A full multiple comparison test on all of the individual instances of sample type, mode of delivery (ortho vs retro), and mode of timing (early vs late) further showed that in 10 out of 16 instances a significant difference at the 5% level occurs between ortho- and retronasal delivery. Significant differences occur in each of the four different samples tested. Signifcant differences between early and late delivery occur in six out of 16 instances. Significant differences between samples at identical mode of delivery and timing of delivery occur between water and both whey protein gels as well as the custard. ANOVAs were used to test for further differences between pairs since these proved more powerful.

Early vs Late Delivery of the Aroma. With the current experimental setup and protocol, it is possible to vary the time between swallowing of the food product and the actual delivery of the aroma pulse. In the experiments described here, we used two intervals for aroma delivery, 1 and 6.5 s after the instruction to swallow. In **Figure 5B**, we show the results (ANOVA) for the data set decomposed between early and late pulse delivery. In this case, the data for the different gels as well as orthonasal and retronasal stimulation were combined. A clear effect of the

moment of pulse delivery was observed, where late delivery was rated higher than early delivery ($F = 6.31$, $p = 0.012$). When we further decomposed the orthonasal and retronasal delivery data into the different food products, we observed that for early delivery of aroma, the custard, water, and WPI samples were all significantly different (custard−water, $F = 22.8$, $p < 0.0001$; water−WPI, $F = 5.39$, $p = 0.0005$; and custard−WPI, $F = 4.49$, $p = 0.036$). In the situation that the aroma was delivered "late", the custard was still significantly different from water ($F = 14.1$, $p = 0.00024$) but not from WPI samples ($F = 42.4$, $p = 0.13$) and the WPI samples were not significantly different anymore from the water sample ($F = 2.28$, $p = 0.10$).

Orthonasal vs Retronasal Delivery of Aroma. Another objective of the experiments described here was to further the importance to investigate cross-modal texture−aroma interactions on the level of orthonasal and retronasal stimulation. First, we analyzed the difference between orthonasal and retronasal stimulation when the data for early and late delivery as well as for the different food gels are combined (**Figure 5C**). Subjects rated the intensity lower when the aroma pulses were delivered retronasally as compared to orthonasal delivery ($F = 59.4$, $p < 0.0001$). The difference in intensity between orthonasal and retronasal delivery of the aroma pulse was approximately three times as large as the reported difference between the early and the late administration of the pulse. When we further decomposed the orthonasal and retronasal delivery data into the different food products that were used, no significant effect of texture on the observed perceptual difference between orthonasal and retronasal aroma delivery occurred. In **Figure 5D**, the same trend in aroma intensity perception can be observed for water, WPI gels, and custard for both orthonasal and retronasal delivery of the aroma.

DISCUSSION

Orthonasal olfactory perception occurs during sniffing of odors. It is primarily important before eating or drinking a food product. It enables a person to assess the quality of food before actually consuming it. Retronasal perception occurs during oral processing and swallowing of food products. It was shown in previous aroma release measurements that swallowing determines for a large part the in vivo retronasal aroma release especially for (viscous) liquids, which undergo only limited oral processing (*22*, *26*, *27*), showed the formation of a thin layer of food product on the surface of the pharynx. During exhalation following a swallow, a steep gradient in aroma concentration exists between the thin liquid layer on the surface of the pharynx on one hand and the exhaled air that passes this surface on the other. Much of the aroma present in the thin layer will be released into the air stream and reach the olfactory epithelium in the nose (*20*, *22*, *28*). In the present study, we aimed to deliver an aroma pulse with controlled intensity, duration, and timing to the nose, in either an orthonasal or a retronasal fashion, separately from the texture stimulation in the oral cavity. The study provided the following results: (i) Aroma delivered in an orthonasal fashion is rated as more intense than aroma delivered in a retronasal fashion; (ii) As compared to the presence of water in the mouth, eating of a semisolid food like a custard or a protein gel produces a decreased intensity perception of a concomitantly administered odor; (iii) There appears to be no significant effect of the mode of aroma delivery (either orthonasal or retronasal) on the observed cross-modal effect of texture on aroma intensity; and (iv) late delivery of the aroma after swallowing produces higher aroma intensities than early delivery of the aroma after swallowing and decreases the cross-modal effects.

The result that aroma delivered in an orthonasal fashion is rated as more intense than aroma delivered in a retronasal fashion (**Figure 5C**) is in line with previous work (*25*, *29*, *30*). In our case, the difference in aroma intensity between orthonasal and retronasal delivery of the aroma pulse was relatively large as compared to the intensity difference between the early and the late administration of the pulse (**Figure 5B**), which was about three times smaller. The difference in intensity between ortho- and retronasal administration may be explained, at least in part, by the nasal anatomy. It has been shown that odor thresholds or odor identification are correlated to the volume of the anterior portion of the nasal cavity (*31*, *32*). Differences in airflow may result in different local concentrations that depend on the exact nasal anatomy. Furthermore, work from Sobel et al. suggests that slight anatomical differences between the left and the right nostrils leading to lateralized differences in air flow may produce significant differences in odor quality (*33*). Moreover, Mozell and co-workers proposed a "chromatographic model" of olfaction. This model suggests that the direction of odorant flow across the olfactory epithelium, from front to back or the reverse, may change the perception of odorants (*34*) due to the zonal organization of olfactory receptor neurons within the olfactory epithelium (*35*). It seems possible that orthonasal presentation of an odor produces a pattern of mucosal activation that is different from the pattern induced through retronasal presentation of the same odor. These different patterns might be processed more or less effectively, which may help explain the observed differences in perception between orthonasal and retronasal stimulation (for a review, see ref *36*).

The present results show that intensity of the strawberry aroma decreases when a custard or whey protein gels have been orally processed before aroma administration in comparison to plain water (**Figure 5A**). This is in line with previous reports in which cross-modal aroma−texture interactions were hypothesized based on in vivo APCI-MS studies in combination with sensory ratings of protein gels and viscous solutions (*7*, *9*). The fact that we do not observe a significant difference between the two types of protein gels may indicate that the difference in firmness was too small. In contrast to the present study where we chose not to vary the protein concentration of the gels, for our previous experiments, protein concentrations were varied (*7*) to obtain gels with more extreme differences in texture. We note that prior to consumption the protein gels were more firm than the custard in the sense that they are self-supporting gels requiring a penetration force of 25−50 g for fracture. However, during oral processing, the custard remains much thicker and more viscous as compared to the protein gels and consequently produce a much thicker mouth feel. It has been shown recently (*37*, *38*) that for starch-based vanilla-flavored custard desserts, extensive amylase activity in saliva results in increased melting and decreased thickness sensations. Thus, physiological factors may have led to the difference in perceived texture among subjects and may explain some of the observed judge*sample interactions (*39*).

Besides the hypothesis that the perceived texture has a cross-modal effect on aroma intensity, other factors may also contribute to the differences observed in this study. It is possible that a difference in sweet perception is at least partly responsible for the differences in aroma intensities. Although the samples were designed to have similar sweetness intensity, aspartame (whey protein gels were sweetened by aspartame) and sucrose (the custard sample were sweetened by sugar) can be perceived slightly different. With regard to sweetness, it is surprising that the intensity of the strawberry aroma just after having the

unsweetened water sample in the mouth was rated highest. Previous publications reported that sweetened products increase the intensity of a congruent aroma like strawberry (*10*, *40*), as compared to unsweetened products with identical texture. Building on this, it may be that a congruency between specific textures and aroma perception exists but we have at present no further evidence for this hypothesis. In the present study, no direct comparison between similar textures is made with respect to sweetness. We further verified this in an additional test with 11 panelists in which the aroma intensity of the original custard was compared with that if water to which aspartame was added. The amount of aspartame added (0.028%) now was in line with the published sweetness factor of 180. Again, the aroma intensity after oral processing of water was perceived as higher than after oral processing of custard ($F = 7.45$, $p = 0.007$).

When we further decomposed the data for orthonasal and retronasal delivery into the different food products that were used, we found no difference for the effect that the oral processing of the food products has an aroma intensity between orthonasal and retronasal delivery (**Figure 5D**). This result implies that the interaction between the perceived texture and the aroma of these types of foods occurs at a level beyond the stimulation of the olfactory epithelium. When the pulse arrives with a delay of several seconds after swallowing, the odor intensity was higher as compared to the early administration (within 1 s after swallowing) of the odor. Some of the subjects indicated that the delay between the swallowing and the late pulse delivery was "unnaturally" long and that they were waiting for it to arrive. Therefore, it may be speculated that for the late presentation subjects had time to prepare themselves and in the absence of a texture in the mouth, focus their attention on the olfactory stimuli following swallowing. This appears to relate to attention effects, which have been described for the olfactory modality (*41*, *42*). It seems logical to expect that a cross-modal interaction between perceived texture and aroma is smaller as the stimuli are administered further apart in time. Indeed, the differences in aroma intensity between the products are larger and more significant when the aroma profile is administered directly after swallowing as compared to late administration at 6.5 s after swallowing. Because the panelists were able to see the products, we cannot exclude the effect of visual cues on aroma perception.

To summarize, the present experiments demonstrate that it is possible to deliver an aroma profile in a time- and concentration-controlled fashion that closely resembles the nose space concentration during normal eating, while administering foods of different textures to human subjects. Our experiments show that the intensity of the aroma is increased when the delay between swallowing and delivery of the aroma profile is increased. We further confirm that retronasal stimulation leads to a significant decrease of aroma intensity as compared to orthonasal stimulation. This effect is three-fold larger than the difference that results from early or late stimulation. Our results suggest that differences in perceived texture can indeed lead to differences in aroma intensity by cross-modal psychophysical interactions. Using the current experimental protocol, these cross-modal texture−aroma interactions do not depend strongly, if at all, on orthonasal or retronasal stimulation, which may point to a higher level central nervous origin of this phenomenon. However, more experiments are necessary to obtain more insight in this issue. Variations in aroma delivery (timing and profiles) and products with more extreme texture will be studied soon.

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