Article

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Abstract

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HE, Wei, *et al*. Sensory-specific satiety: Added insights from autonomic nervous system responses and facial expressions. *Physiology & Behavior*, 2017, vol. 170, p. 12-18

DOI : 10.1016/j.physbeh.2016.12.012

Physiology & Behavior 170 (2017) 12–18

Contents lists available at ScienceDirect

Physiology & Behavior

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

Sensory-specific satiety: Added insights from autonomic nervous system responses and facial expressions

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HIGHLIGHTS

- We measured sensory-specific satiety with autonomic nervous system responses and facial expressions.
- Consumption of the test meals resulted overall in increased heart rate, reduced skin conductance and skin temperature, as well as intensified disgusted facial expressions.
- Skin conductance and skin temperature reflected effects of sensory-specific satiety.
- Sad and angry facial expressions showed effects of sensory-specific satiety.

ARTICLE INFO

Article history:
Received 13 April 2016
Received in revised form 11 August 2016
Accepted 9 December 2016
Available online 14 December 2016

Keywords:
Sensory-specific satiety
Skin conductance
Skin temperature
Heart rate
ANS responses
Facial expressions

ABSTRACT

As a food is consumed, its perceived pleasantness declines compared to that of other foods. Although this phenomenon, referred to as sensory-specific satiety, is well-established by means of measuring food intake and pleasantness ratings, this study was aimed at gaining more insight into the mechanisms that underlie such cognitive output behavior using two measures used in (food) emotion research, namely Autonomic Nervous System (ANS) responses and facial expressions. Twenty-four healthy female participants visited four times in a hungry state, in which they received 4 different semi-liquid meals (2 sweet and 2 savory) delivered via a time-controlled pump leading to sensory-specific satiety. Before and after the meals they were presented with a sip of all four different test meals where ANS responses (heart rate, skin conductance and skin temperature) and facial expressions were recorded. As expected, pleasantness ratings showed a significant decrease after eating the same meal or a meal similar in taste (sweet or savory) ($p < 0.001$), and less decrease after eating a meal with a different taste. In general, consumption of the test meals resulted in increased heart rate, reduced skin conductance and skin temperature, as well as intensified anger and disgusted facial expressions ($p < 0.05$). In addition, skin conductance, skin temperature, sad and angry expressions also showed effects reflecting sensory-specific satiety. In conclusion, ANS responses and facial expressions indicate that sensory specific satiety of foods 1) not only reduces the food's pleasantness but also arousal and 2) are possibly mediated by changes in food emotions.

1. Introduction

In the modern world, where food is plentiful, cheap and energy-dense, we eat not only to fulfil nutritional needs, but also for pleasure. Sensory cues, such as taste, smell and sight of food, contribute a great deal to such pleasure derived from eating. Sensory characteristics and their subsequent physiological and neurobiological effects are thus important determinants in regulating when, what and how much we eat [1,2]. However, unlike nutritional composition, pleasantness or hedonic value is not a fixed property of a food, but a momentary evaluation which can change with experience [3]. The pleasantness of a food (or similar foods) decreases during and shortly after consumption, whereas the pleasantness of other dissimilar foods not consumed remains unchanged or decreases much less. This phenomenon was first reported in humans by Rolls and her colleagues [4] following earlier work in animals by Le Magnen and others [5,6]. Rolls found that the rapid decline in pleasantness accompanying ingestion depended more on the sensory properties of foods than on the nutrient composition or post-ingestive effects. As a result, they coined the term "sensory-

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http://dx.doi.org/10.1016/j.physbeh.2016.12.012

specific satiety". Sensory-specific satiety may thus contribute to the termination of eating due to decreased pleasantness of a single food [7], but may also enhance intake through a composite meal [8,9]. So far, taste [10], olfactory [11], texture [12] and appearance-specific satiety [13] have been demonstrated.

The decrease in pleasantness is not the only consequence of consumption. Consumption also leads to sensations of fullness which have physical and psychological components [14–16]. Fullness has been described by physical components such as the feeling of something in the stomach and stretch in the stomach, and by psychological components such as satisfaction, comfort, and ability to focus on tasks [17]. Self-reported satiety measures have included scales related to hunger and fullness feelings, desires to eat, prospective consumption, and satisfaction. In contrast, sensory-specific satiety has mainly been investigated using pleasantness ratings, subsequent food intake and few neuroimaging studies [18,19]. All in all, satiety and sensory-specific satiety may comprise of a multitude of feelings that cannot be fully captured with such (limited) self-report measures that are frequently used.

Alternative measures that are not based on self-report but on facial expressions or on responses of the autonomic nervous system (ANS) have not yet been used in studies of satiety and sensory-specific satiety, but may prove to be relevant. Facial expressions and ANS responses have been extensively used in emotion studies. As alluded to above, emotional responses play an important role in eating behavior in everyday life [20], both consciously and unconsciously. One way to investigate such emotional responses is through measuring facial expressions [21]. Steiner [22] already documented that newborns could clearly show their emotional responses to liked or disliked taste through facial expressions. Furthermore, autonomic nervous system responses can also distinguish among emotions, as reported by Ekman [23]. Previous studies [24–27] demonstrated that foods or food cues that were liked or disliked by participants elicited differential responses of the ANS as well as different emotional responses measured by facial expressions. It was concluded that autonomic responses provide additional information on food preferences relative to more traditional hedonic tests. Facial expressions may reflect internal appraisals going on in the body during evaluating (anticipating) food. The actions that result from these appraisals are then executed by the autonomic nervous system resulting in the appropriate behaviors that can be roughly categorized into fight or flight reactions: The flight system is mainly active in those situations involving threat, with the resulting behaviors aimed at withdrawal, attack, and escape. In contrast, the fight system is mainly active in situations "that promote survival including sustenance, procreation, and nurturance, with a basic behavioural repertoire of ingestion, copulation, and caregiving" (Bradley et al., 2001). The autonomic nervous system may this be considered a goal-direct system, acting as intermediate between internal emotional feelings, and external output behavior (such as liking responses, or the decision to continue or stop eating). Therefore, both ANS responses and facial expressions may provide additional insights into the mechanisms underlying sensory-specific satiety. We hypothesize that ANS responses at the start of a meal reflect approach behaviors whereas those at the end of the meal reflect avoidance reactions.

The present study assessed the effects of sensory specific satiety with traditional hedonic measures, as well as with facial expressions and ANS responses, using four different test foods that can be organized according to similarity in taste (same, similar, or different). The following hypotheses were tested:

1. ANS responses and facial expressions change with consumption. No changes would indicate that these responses do not reflect sensory-specific satiety.
2. ANS responses and facial expressions change with consumption but the result patterns are different than found for the hedonic measures. In this case ANS responses and facial expressions reflect satiety but not sensory-specific satiety.
3. ANS responses and facial expressions change with consumption and show similar result patterns as found for hedonic measures. In this case, ANS measures and facial expressions reflect satiety and sensory-specific satiety.

2. Material and methods

2.1. Experimental design

The study design was a within-subject counterbalanced cross-over intervention experiment with four semi-liquid foods used to induce and assess sensory-specific satiety (See Fig. 1). All participants visited four times. In each visit, participants first tasted single sips of four test foods (two sweet, two savory, see Table 1) before they consumed one of the four foods until pleasantly satiated by means of time-controlled consumption. Finally, they tasted single sips of the four test foods again. Before, during and after consumption, pleasantness, emotional and physiological measures were taken in response to tasting a sip of the four different test foods.

2.2. Participants

Twenty-four females were recruited from the participant pools of Food and Biobased Research and the Division of Human Nutrition, part of Wageningen University and Research Centre. Participants were self-reported healthy, had a normal weight (BMI 18.5–25 kg/m^2, mean ± SD 21.2 kg/m^2 ± 1.7), and were aged between 18 and 32 year (mean ± SD 23.0 year ± 3.4). Exclusion criteria were disliking any of the foods used in the study (pleasantness score < 5 on a 9-point hedonic scale), restrained eating (Dutch Eating Behavior Questionnaire (DEBQ) score > 2.79), gained or lost > 5 kg weight during the last year, having a lack of appetite, smoking, having gastrointestinal illness, having diabetes, having thyroid disease or any other endocrine disorder, having hypertension, suffering from kidney diseases and being pregnant or breast feeding. Participants were unaware of the aim of the research. Detailed information regarding the experiment was given and an informed consent form was signed by all participants prior to testing. The study was approved by the Medical Ethical Committee of the Wageningen University (NL48361.081.14).

2.3. Test foods

Four test foods, two sweet and two savory, had been developed previously in pilot studies with respect to similarity in texture, serving temperature and energy density (1 kcal/g), as well as pleasantness, familiarity and perceived thickness. Semi-liquid foods that can be ingested through a straw without chewing were chosen to minimize motor activity that may produce artefacts in ANS responses and facial expressions. The recipes of the test foods used in this study are shown in Table 1. All of the test foods were freshly made within 36 h and taken out from refrigerator 1.5 h before each session.

2.4. General procedure

Participants were scheduled to always visit at the same time on test days, and were instructed not to eat (only drink water) at least 3 h before each session started. After participants were seated in a comfortable chair and placed with electrodes for physiological measurements, the experimenter explained the experimental procedures and instructed participants to orient towards a laptop monitor with instructions and a webcam at eye-level (1 m viewing distance). They were asked to face the camera while tasting and consuming the foods to ensure recognition by the FaceReader software.

On the right-hand side of the participant, four pairs of opaque cups (numbered 1 to 8) with a straw were placed, filled with the four test foods. Participants were instructed to take a sip from a cup and rate

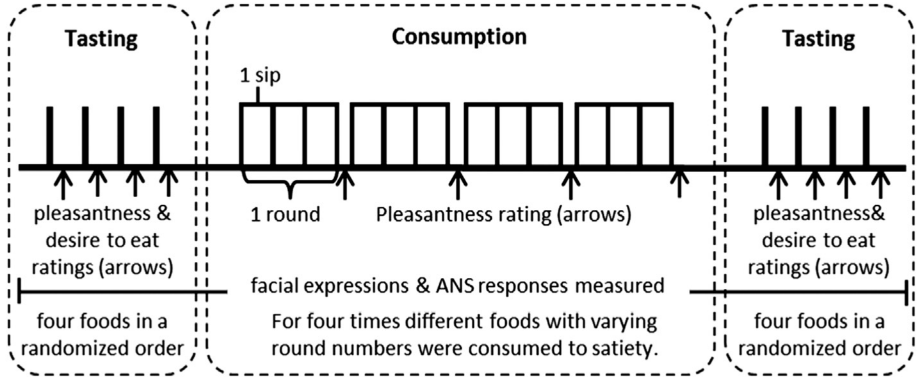

Fig. 1. Schematic representation of the experimental procedure followed during one experimental session. In total, participants took part in 4 sessions; in each of them they received a different test food to eat until pleasantly satiated.

pleasantness and desire to eat, for all four test foods in a randomized order. All instructions were presented on the laptop including which cup to pick, when to sip and how to rate the questions.

After rating all four test foods, participants were asked to rate their hunger and were instructed to put a small tube in their mouth to start consumption. When they pressed ‘Start’, a time-controlled pump (Watson-Marlow, type 323Du, Watson-Marlow Bredel) delivered sips of one of the four test foods to their mouth (3 g/s, 4 s duration, 12 g/sip, 15 s interval between two sips). After every three sips, participants rated their pleasantness for the test food and indicated whether they wanted to continue eating, until they felt comfortably satiated. Afterwards, they rated their hunger feelings again, and repeated tasting and rating all four test foods from the cups.

During the whole session, participants' physiological responses and facial expressions were continuously measured.

2.5. Measurements

2.5.1. Pleasantness and desire to eat ratings

A digital visual analog scale (VAS) of 100 mm was used to rate pleasantness (from ‘very unpleasant’ to ‘very pleasant’), desire to eat (from ‘not at all’ to ‘very much’), hunger (from ‘not hungry’ to ‘very hungry’), fullness (from ‘not full’ to ‘very full’), as well as prospective consumption for the four foods (from ‘not at all’ to ‘very much’).

2.5.2. Physiological responses

Physiological measures were transduced using a BIOLAB (Version 3.0, Mindware Technologies Ltd.) physiological system, designed for use in life science investigations, and includes heart rate (HR) expressed in beats per minute, using electrodes placed on the palm of the left hand of the participant; skin conductance level (SCL) expressed in μSiemens measured via surface electrodes covered with electrode gel and placed on in the palm of the left hand; skin temperature (ST) in degrees Celsius using a surface sensor placed on the subject's middle finger of the left hand. Electrodes were used with a surface of 4.1 cm^2 and filled with 1% Chloride wet gel. Signals were transferred to the Acquisition Unit (16-bit A/D conversion) and stored on computer hard disk (sampling rate 500 Hz/s). Electrocardiographic R waves were detected offline, and intervals between heartbeats were converted to HR, expressed in beats per minute (BPM). SCL activity was recorded by the constant voltage method (0.5 V).

2.5.3. Facial expressions

Facial expressions of participants were filmed with a Logitech C600 webcam, mounted on top of a computer monitor placed in front of the participant. Facial expression data were automatically analyzed per time frame of 0.04 s by FaceReader 4 (Noldus Information Technology, Wageningen, The Netherlands) in three steps. The face is detected in the first step using the Viola-Jones algorithm [28]. Next, the face is accurately modelled using an algorithmic approach [29]. Based on the Active

Table 1
Information of four test foods, including recipe (g/100 g), sensory ratings (mean ± SD, based on pilot studies), intake (g, mean ± SD) and time to satiety (minutes, mean ± SD), as well as hunger and fullness ratings of pre- and post-consumption. Note that the test foods were similar in texture, serving temperature and energy density (1 kcal/g).

Category		Savory semi-liquid food				Sweet semi-liquid food			
Name		Gazpacho		Pea-spinach soup		Mango smoothie		Strawberry juice	
Recipe		Tomato juice	38.9	Fresh spinach	20.6	Canned mango	41.1	Frozen strawberry	39.5
		Peeled cucumber	26.0	Canned peas	20.6	Water	23.0	Strawberry juice	29.2
		Sieved tomato	11.3	Water	27.4	Fantomalt	16.1	Fantomalt	15.2
		Fantomalt	9.5	Peeled cucumber	16.5	Frozen mango	11.5	Canned strawberry	13.2
		Grilled pepper	8.7	Sour cream	9.2	Quark (full fat)	8.2	Honey	2.9
		Olive oil	5.2	Olive oil	4.1	Salt	0.1		
		Red wine vinegar	0.3	Fantomalt	2.3				
		Salt	0.1	Stock powder	0.4				
Pleasantness		5.9	1.0	6.1	1.2	7.1	1.0	7.7	1.2
Sweetness		4.6	1.5	3.2	1.6	7.0	1.0	7.5	1.6
Savoriness		6.5	1.5	6.5	1.3	2.3	1.6	2.1	1.3
Thickness		5.1	1.3	5.3	1.5	7.0	1.2	5.5	1.5
Intake (g)		178.0	135.5	164.4	129.4	226.8	137.1	220.0	167.8
Time to satiety (min)		8.9	3.7	8.6	3.3	9.7	3.7	9.6	4.5
Hunger	Pre	76.0	10.3	70.2	10.5	73.3	9.6	73.8	14.9
	Post	42.7	19.2	41.5	19.6	39.4	19.6	36.0	23.6
Fullness	Pre	21.9	14.7	25.0	13.1	24.0	10.2	26.0	19.2
	Post	53.3	18.0	58.9	17.2	59.3	19.7	62.5	18.8

Appearance method described by Cootes and Taylor [30] the model is trained with a database of annotated images that describes over 500 key points in the face and the facial texture of the face. The key points only describe the global position and the shape of the face, but do not give any information about, for example, the presence of wrinkles and the shape of the eye brows. These are important cues for classifying the facial expressions. Finally, the actual classification of the facial expressions is based on an artificial neural network trained with 10,000 manually annotated images. The face classification provides the output of six basic expressions (happy, sad, angry, surprised, scared, disgusted) and one neutral state on the basis of the Facial Action Coding System developed by Ekman and Friesen [31]. FaceReader scores for each emotional expression range from 0 (emotion is absent) to 1 (fully present) and is based on intensity judgments of human experts. FaceReader allows for the simultaneous presence of multiple emotions. A more detailed description of the science behind FaceReader can be found at: http://info.noldus.com/free-white-paper-on-facereader-methodology/, or see [32,33].

2.6. Data analysis

Only tasting data collected before and after consumption to satiety were analyzed for this paper, in order to assess effects of sensory-specific satiety. Based on the degree of similarity between tasted and consumed food, three conditions were defined: same taste (the tasted food was the same as the food eaten to satiety, e.g. taste gazpacho and consume gazpacho); similar taste (the tasted food was similar in taste (sweet or savory) to the food consumed to satiety, e.g. taste gazpacho and eat pea-spinach soup); and different taste (the tasted food was different in taste from the food consumed to satiety, e.g. taste gazpacho and eat mango smoothie).

The moments that test foods reached the lip of participants were marked manually as tasting moment (T0) in the video recordings. Video data was combined with a trigger in ObserverXT 11 software (Noldus Information Technology) each time when a test food was tasted. Synchronization of data signals was automatic in the case of the skin conductance level, heart rate and skin temperature and video signals. Off-line, the close-up images of the subject's face were then analyzed using FaceReader 5.0 software (Noldus Information Technology), and the resulting log file were imported in the Observer data file.

We conducted repeated measures ANOVAs (IBM SPSS Statistics 21.0, IBM Corporation, Armonk, USA) for a 2 (type of ratings) by 2 (pre-/post-consumption) by 3 (conditions) within-subject design to compare subjective ratings of pleasantness and desire to eat taken before and after consumption.

In our previous studies [25,26,34], we showed raw data for the physiological parameters and facial expressions, demonstrating that most variation typically occurs between 1 and 5 s. In order to investigate how heart rates change before and after consumption, we extracted heart rate data within a time window of 20s (with the tasting moment in the middle) for both pre- and post-consumption. Before and after tasting, heart rate showed a biphasic response, including a decreasing phase of 5 s before tasting and an increasing phase of 5 s after tasting (See Fig. 3). The decreased HR is during an anticipatory phase, since participants was instructed to take the cup and put the straw in their mouth just before sipping. Thus we took the data of an earlier time window ($-10 \sim -5$ s) as baseline and subtracted it from corresponding data of the 5 s time window after tasting. We then subtracted pre-consumption data from post-consumption, and averaged these deltas over all participants. The averaged post minus pre consumption deltas were calculated for all outcome measures. We did similar calculations for skin conductance level, skin temperature and facial expressions data except taking 5 s time window before tasting ($-5 \sim 0$ s) as baseline.

Finally, Mixed Models analysis was applied (IBM SPSS Statistics 22.0, IBM Corporation, Armonk, USA) for ANS responses and facial expressions with a 2 (pre- and post-consumption) by 3 (same, similar and different taste conditions) within-subject design. A p-value of 0.05 was considered significant.

3. Results

3.1. Pleasantness and desire to eat ratings

Pleasantness and desire to eat ratings decreased significantly after consumption to satiety ($F(1, 23) = 89.4$, $p < 0.001$). Moreover, there was a significant interaction between pre-/post-consumption and conditions ($F(2, 46) = 32.5$, $p < 0.001$). Post-hoc tests showed that both ratings declined more for the same taste condition than for the similar taste condition (all $p < 0.001$), and also declined more for the similar taste condition than for the different taste condition (all $p < 0.001$, see Fig. 2). Desire to eat ratings in all conditions decreased more than the corresponding ratings in pleasantness ratings ($F(2, 46) = 7.6$, $p < 0.01$, see Fig. 2).

3.2. Physiological responses

Results showed that over all conditions heart rate increased significantly after consumption ($F(1, 134) = 29.6$, $p < 0.001$). Furthermore, compared to pre-consumption no significant difference between conditions were found (See Fig. 4A), indicating no signs of sensory-specific satiety, but of general satiety.

Both skin conductance level ($F(1, 138) = 30.0$, $p < 0.001$) and skin temperature ($F(1, 138) = 29.8$, $p < 0.001$) decreased significantly after consumption to satiety. Furthermore, both responses also showed an interaction between conditions and pre-/post-consumption (SCL: $F(2, 69) = 2.9$, $p = 0.019$; ST: SCL: $F(2, 69) = 4.4$, $p = 0.012$). Post-hoc tests showed that skin conductance level decreased more for the similar and different taste conditions than for the same taste condition ($p < 0.05$, see Fig. 4B). Skin temperature decreased most for the different taste condition and least for the same taste condition ($p < 0.001$, See Fig. 4C).

3.3. Facial expressions

Facial expressions before and after consumption varied in their effects. All expressions varied with the type of test food. Expressions of disgust intensified after consumption ($F(1, 138) = 8.4$, $p < 0.01$). In addition, angry ($F(2, 69) = 7.5$, $p < 0.01$) as well as sad ($F(2, 69) = 14.6$, $p < 0.001$) expressions showed effects of condition (in interaction with pre-post consumption, see Fig. 5): Angry expressions increased after consuming similar or same test foods, and decreased for the different food. The opposite occurred for sad expressions, which decreased for the same and similar condition, but increased after consuming different test foods.

4. Discussion

The present study tested the effects of Sensory-specific Satiety (SSS) with traditional hedonic measures, as well as with facial expressions and ANS responses to test the three hypotheses outlined in the introduction. The traditional pleasantness measure showed the result pattern commonly found for SSS, namely the largest decrease in pleasantness after consumption of the same food, a smaller decrease after consumption of a similar food and the least decrease after consumption of a different food. This demonstrates that SSS indeed was induced in this study, at least when traditional hedonic measures are used. Moreover, desire to eat ratings changed more than pleasantness ratings for all conditions. This difference may reflect the distinction between processes associated with affective versus motivational consequences of ingesting food, in short, liking versus wanting [35]. Mela [3] in a review defined ‘liking’ as the immediate experience or anticipation of pleasure from the sensory stimulation of eating a food, and

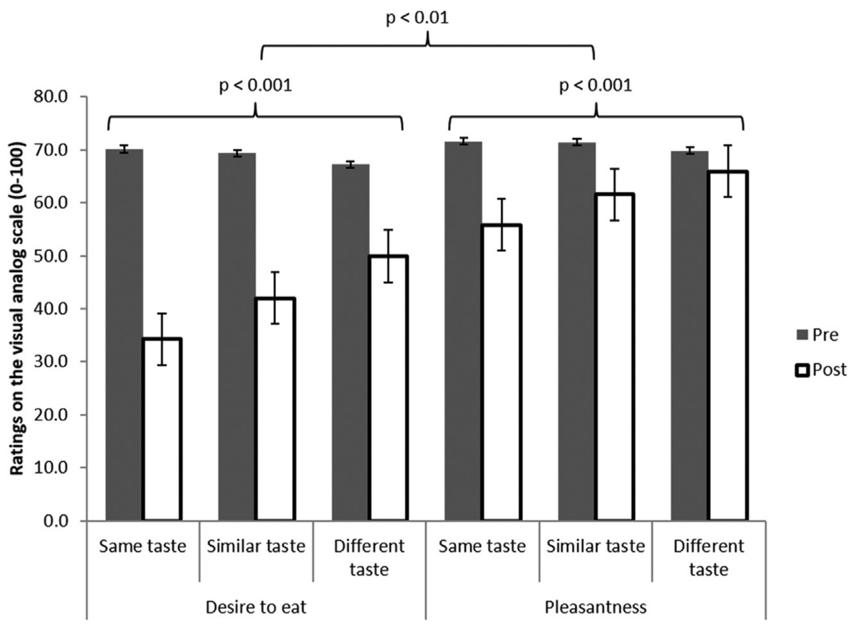

Fig. 2. Pleasantness and desire to eat ratings of the same, similar and different taste conditions for both pre- and post-consumption. Error bars represent standard error of the mean.

'desire' or 'wanting' as the intrinsic motivation to engage in eating a food. It seems plausible that the motivation to eat declines more than the appraisal of sensory stimulation during consumption. In addition, all of the absolute pleasantness ratings after consumption were still above neutral, whereas the absolute desire to eat ratings declined to below neutral, even for uneaten foods (See Fig. 2). This distinction indicates that at the beginning of eating, appraisals of liking and wanting were similar to each other. During the process of consumption, however, internal motivational state may contribute more than that of sensory stimulation to the termination of a meal.

Facial expressions and ANS responses also change with consumption which indicates that they reflect satiety, and for specific facial expressions and ANS measures also (but not necessarily) sensory-specific satiety. In general, consumption was associated with increased heart rate, decreased skin conductance and skin temperature, and intensified expression of disgust, irrespective of the specific food. Increased heart rate had also been found in previous food studies [36–39] and probably reflects the increased motor activity associated with eating and may be unrelated to SSS. Skin conductance reflects arousal and reduced skin conductance and skin temperature after consumption probably reflects the increased familiarity with the test situation resulting in lower physiological arousal. In contrast to the lowering effect of satiety on physiological arousal, facial expressions associated with arousal [40,41] intensified with satiety. The differences between ANS results and facial expressions may reflect differences between their mechanisms. Facial expressions are rapidly changing and reflect the results of ongoing appraisals of aspects such as the food's novelty and pleasantness. ANS responses probably reflect a goal-directed system that determines whether consumption is continued or stopped. This determination is probably based on the multiple appraisals reflected by facial expressions whereby different appraisals probably carry different (unknown) weights. These differences in functions and mechanisms between ANS responses and facial expressions may explain some of their apparent contradictories. In summary, however, our results suggest that satiety results in a shift in emotions associated with shifts in the foods' pleasantness as well as the arousal triggered by the food.

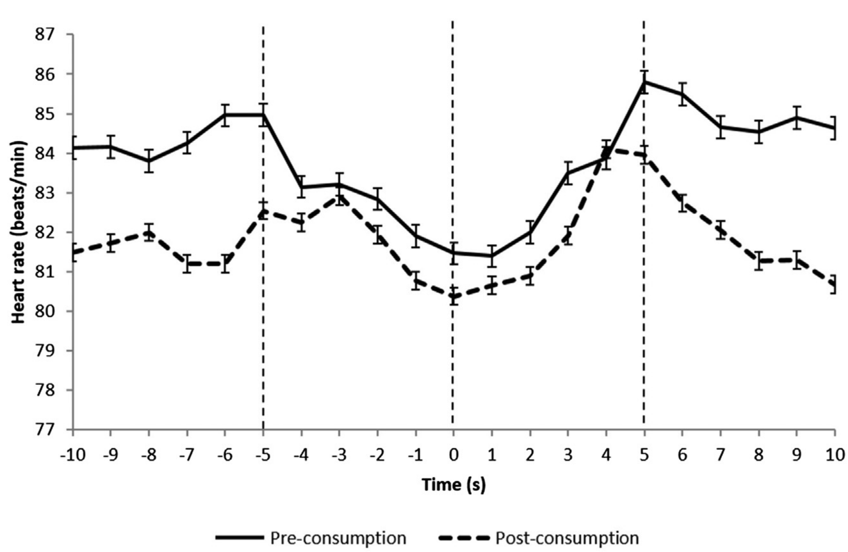

Fig. 3. Averaged heart rate of pre- and post-consumption over 10s before and after tasting moment. (The broken lines indicate time point of 0 s, −5 s and 5 s, respectively. Error bars represent standard error of the mean.)

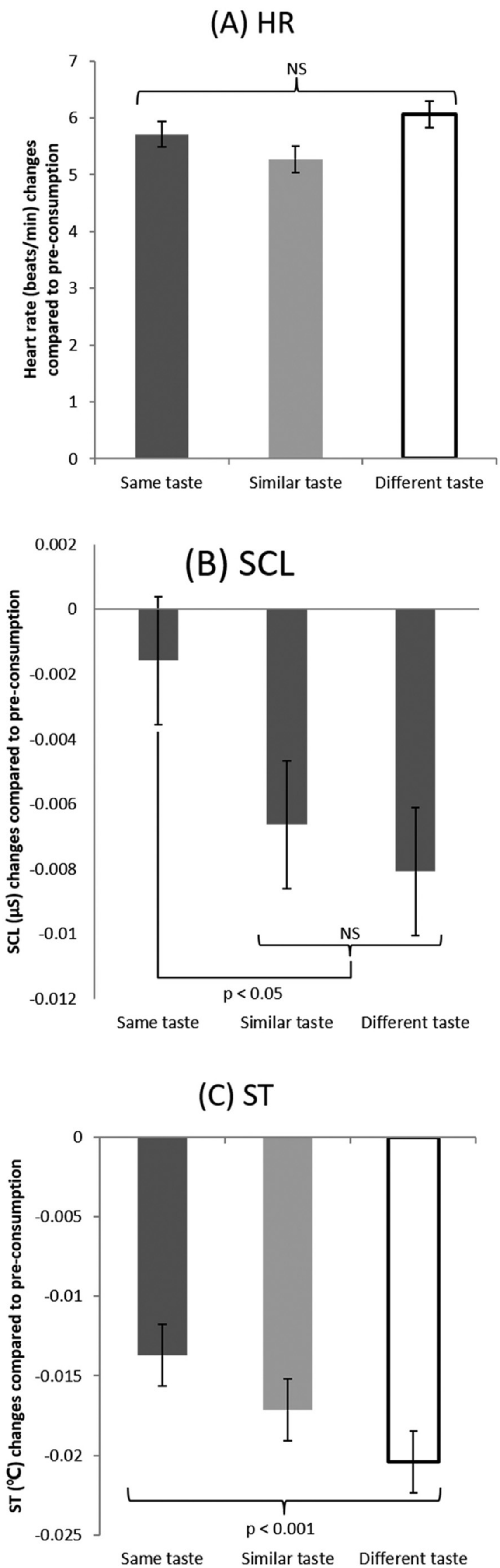

Fig. 4. Changes in (A) heart rate (B) skin conductance level (C) skin temperature for the same, similar and different taste conditions compared to pre-consumption after subtracting from baseline. Error bars represent standard error of the mean.

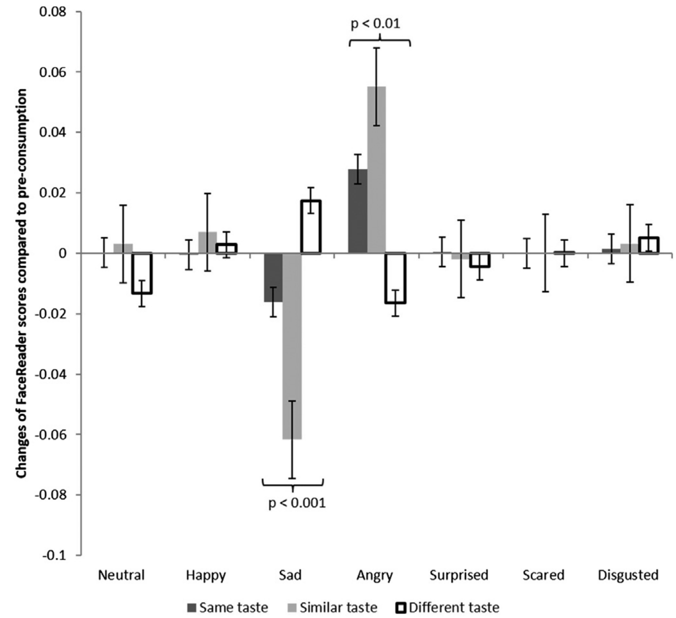

Fig. 5. Changes of facial expression scores for the same, similar and different taste conditions compared to pre-consumption after subtracting from baseline. Error bars represent standard error of the mean.

Not only are specific ANS measures and facial expressions sensitive to variations in satiety but also to SSS. The decrease in skin temperature and SCL are larger after consumption of a different food than after consumption of the same or similar food. As skin conductance typically increases in response to novel stimuli, as an orienting response, this decrease can be interpreted as sign of familiarity, or perhaps even boredom, with the (same) food. Similarly, facial expressions of anger and sadness after consumption of a different food differ from the expressions after consumption of the same of similar food. Consumption of the same or similar food is associated with reduced sadness and intensified anger indicating a shift towards higher arousal, and may signal 'being fed up' with the test food. A reversed shift towards lower arousal is observed after consumption of a different food.

In the present study, sensory-specific satiety was induced by ad libitum consumption in which participants were instructed to consume as much as they like. Moreover, we adopted three tasting conditions based on the same foods, similar uneaten foods and different uneaten foods, compared to the food consumed to satiety. This study design allows us to disentangle effects related to satiety versus sensory-specific satiety. Clearly, the current study used an experimental, not real-life setting, in which participants sipped semi-liquid foods through a straw, and results may thus not be directly translatable to real life. Despite this limitation, this setup was successful in inducing SSS, given the explicit liking ratings. Further exploration may focus on dynamic emotional changes during consumption in more natural eating situations. Additionally, our used methods (e.g. FaceReader) are able to recognize basic emotions, but not others that might be relevant in eating behavior (such as satisfaction, guilt). Whether all possible emotional expressions can be categorized by these six emotions remains a matter of debate (e.g. [34]). For the present study, the fact that FaceReader is able to automatically monitor (changes in) expressions was more important than the exact interpretation of these expressions in underlying emotions. Given the novel combination of methods and study design, we feel we have adopted a good way to start explorations in the field of emotions and eating behavior.

To conclude, in the present study we were able to replicate the classic, unidimensional effects of sensory-specific satiety on food's liking, using a controlled experimental approach. The ANS results and facial expressions of this study corroborate these hedonic effects, but in addition, suggest that sensory-specific satiety effects also involve other dimensions related to arousal and hedonics that are mediated by underlying emotional appraisals.

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