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ABSTRACT

Some odors have a taste dimension likely due to repeated experiences in food with tastes. These odors can significantly enhance the related taste perception; this phenomenon is called Odor-Induced Taste Enhancement (OITE). The study aimed to determine odor-induced taste enhancement (OITE) differences between obese (OB) and normal-weight (NW) people. We hypothesized that OB would perceive a higher sweet taste enhancement than NW. We also tested salty taste enhancement without an oriented hypothesis. 43 NW and 38 OB took part in ranking tasks and evaluated OITE in 13 sweet and 4 salty solutions. The sweet base solutions were apple juice (Aj), cocoa (Coc) and water. The odorants were vanillin, ethyl-vanillin, french vanilla, two lychee odorants, and furaneol. The salty base solutions were a green-pea soup and water, and the odorants were smoky bacon smoked garlic odorants. Each ranking was performed with 4 solutions, 3 with an increasing concentration of salt/sugar, and the fourth contained the lower sugar/salt concentration and one odorant. Participants ranked the four solutions from lowest to highest sweetness/saltiness intensity. As a main result, the OB group perceived OITE more often than NW. The maximum sweetness and saltiness enhancements were observed in OB with vanillin in apple juice and bacon in salty water. Our results also demonstrated that the ranking task efficiently assesses OITE and highlights subtle differences between groups and solutions.

1. Introduction

Food consumption is, in essence, a multisensory experience, if not the most multisensory-one. Besides vision, audition, and touch, food perception involves the chemical senses, including olfaction and taste (Thomas-Danguin, Sinding, Tournier, & Saint-Eve, 2016). These two senses are physiologically separated in terms of receptors, nervous pathways and brain areas, but they interact closely during food perception. How these mechanisms are modulated by individual experience and physiology remains a major question.

During food consumption, tastants and odorants are released into the mouth. While odorants reach the olfactory receptors in the nose through the retronasal pathway, tastants activate taste receptors located mainly on the tongue. The activation of these different receptors is processed in dedicated and well-separated brain areas, resulting in the perception of odor and taste. When taste and odor perceptions repeatedly co-occur, for example, when we frequently eat the same food, the brain unifies both perceptions into a holistic food percept called 'flavor' (Thomas-Danguin, 2009). The integration of odor and taste transfers the taste property to the odor (Stevenson, Prescott, & Boakes, 1995); and the odor can then further enhance the taste. This phenomenon, called "Odor-Induced Taste Enhancement" (OITE), has been largely described usually in simple beverages as sweet (Boakes & Hemberger, 2012; Clark & Lawless, 1994; Djordjevic, Zatorre, & Jones-Gotman, 2004; Labbe, Rytz, Morgenegg, Ali, & Martin, 2007; Schifferstein & Verlegh, 1996; Stevenson, Prescott, & Boakes, 1999) and salty water (Djordjevic et al., 2004; Lawrence, Salles, Septier, Busch, & Thomas-Danguin, 2009; Nasri, Beno, Septier, Salles, & Thomas-Danguin, 2011; Seo et al., 2013). Among the odorants tested, vanilla (Sakai, 2001), strawberry (Djordjevic et al., 2004; Labbe et al., 2007; Schifferstein & Verlegh, 1996), lychee (Stevenson et al., 1999), caramel (Boakes & Hemberger, 2012; Stevenson et al., 1999), bacon, ham and sardine odors (Lawrence et al., 2009; Seo et al., 2013) produced OITE in water-based solutions.

The study of OITE in more complex beverages is challenging because

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of the multiple perceptual interactions that may occur between tastes and odors (Niimi et al., 2014; Veldhuizen, Siddique, Rosenthal, & Marks, 2018). Only a few studies showed OITE in complex beverages (Alcaire, Antúnez, Vidal, Giménez, & Ares, 2017; Barba, Beno, Guichard, & Thomas-danguin, 2018; Labbe, Damevin, Vaccher, Morgenegg, & Martin, 2006; Wang, Bakke, Hayes, & Hopfer, 2019) or food (Frank & Byram, 1988; Proserpio, Laureati, Invitti, Cattaneo, & Pagliarini, 2017). For example, vanilla was shown to enhance the sweetness in cocoa and desserts (Alcaire et al., 2017; Labbe et al., 2006; Wang et al., 2019); caramel, strawberry and peach aromas were shown to enhance the sweetness in fruit juice (Barba et al., 2018); and beef stock enhanced saltiness in green-pea soup (Sinding, Thibault, Hummel, & Thomas-Danguin, 2021).

The primary theory explaining OITE proposes that associative learning between odors and taste occurs due to repeated exposure to concomitant odor and taste (Prescott, Johnstone, & Francis, 2004; Stevenson, Boakes, & Prescott, 1998; Stevenson, Prescott, & Boakes, 1995). To test this theory, subjects were exposed to an unfamiliar odor paired with a taste. For example, participants had to drink a solution of sucrose, once a day, over three days, paired with an unfamiliar odor (e.g., water chestnut or lychee). The odors paired with sucrose were perceived as sweeter after the three co-exposures. A subsequent study by Prescott et al. (2004) showed that even a single exposure was sufficient to induce sweetness association with an odor, when the odorant was smelled orthonasally. Within this study, the authors also demonstrated that using a configural (i.e., synthetic) perceptual strategy during co-exposure was necessary to produce odor-induced sweetness enhancement. Configural perception allows the perception of a single quality on top, or instead of, the different parts/elements of an object (e.g., food produces odors and tastes perceptions but is *in fine* perceived as a single quality, the flavor).

Based on the associative learning theory, Stevenson and collaborators (2016) investigated whether a western diet, which involves high consumption of sweet and fat products, could modulate the OITE. In this experiment, the participants evaluated the sweetness intensity of sweet water with a cherry odorant, and they filled the "Dietary Fat and free Sugar – Short Questionnaire" (DFS-SQ) to characterize their diet. The authors found a maximal cherry-induced sweetness enhancement for a medium odorant concentration when the participants had a healthy diet. In contrast, participants with an unhealthy diet showed maximal cherry-induced sweetness enhancement when the odorant concentration was low. However, they did not find a link between BMI and the questionnaire score.

To the best of our knowledge, only one group of researchers studied odor–taste interaction in people with obesity (OB) compared with normal-weight people (NW) (Proserpio et al., 2017, 2016; Proserpio, Verduci, Zucotti, & Pagliarini, 2021). Interestingly, Proserpio and colleagues (2016) found that only OB participants presented a sweet taste enhancement when a butter odor was added to a custard dessert in the three studies (in one study, this effect was shown only in women). The authors proposed two non-exclusive hypotheses to explain the difference in OITE between groups. First, OB participants would be more exposed to this flavor than NW because they prefer sweet and fat foods that likely contain butter odorant (Bartoshuk, Duffy, Hayes, Moskowitz, & Snyder, 2006). Secondly, OB participants would be more responsive to external food cues such as food odors than NW (Mas, Brindisi, Chabanet, Nicklaus, & Chambaron, 2019), and less responsive to internal cues such as the hunger state (Hanci & Altun, 2016), which could then modulate the OITE. We wished to extend these results by comparing the enhancing effect of 6 sweet and 2 salty-associated odors in OB and NW within simple (water) and complex bases (apple juice, cocoa and green-pea soup). Based on the studies by Proserpio and colleagues, we hypothesized that OB would perceive higher odor-induced sweetness enhancement than NW. Because of the lack of studies on the odor-induced saltiness enhancement in OB, no hypothesis on the difference between groups for the saltiness enhancement could be formulated.

Intensity visual analog scales are traditionally used to assess OITE. However, results from scales are often criticized because they are thought to be biased, notably by halo-dumping effects (Clark & Lawless, 1994). To avoid halo-dumping effects, it is recommended to provide a suficient number of scales to evaluate all the attributes that may be perceived in food (e.g., sweetness, saltiness, sourness, bitterness, odor intensity) However, to measure OITE, evaluating several tastes and odors attributes for one sample is problematic as it forces perception towards an analytical perception that disrupts the configural perception necessary to perceive the flavor (Frank, van der Klaauw, & Schifferstein, 1993). To avoid any putative issue related to visual analog scales, we set up a comparative task based on ranking. The ranking is relevant in the case of OITE studies, as ranking favor an automatic configural processing of the flavor at the expense of visual analog scales that forces analytical processing, especially when multiple attributes have to be evaluated (Prescott, 1999). Because configural processing is necessary for OITE to occur (Prescott, 1999), this method is theoretically more relevant than the visual analog scale to study OITE. The ranking is easily fulfilled as it is a sensory task frequently used in children (Liem, Mars, & de Graaf, 2004) or the elderly (Barylko-Pikielna et al., 2004). Former studies have shown that the ranking task efficiently assessed differences in taste intensities from a set of different orange juices (Carabante & Prinyawiwatkul, 2018) and allowed to measure OITE in water-based solutions (Labbe et al., 2007; Nguyen, 2000). In the present study, a simple ranking task was used involving only 4 samples from the same base to be ranked: 3 reference samples contained an increasing concentration of sugar/salt, and the fourth sample contained the lower tastant concentration and the target odorant. The originality of the study is that we tested OITE i) on a large panel of sweet and salty solutions (n = 17), ii) on a specific population that is likely more prone to experience OITE (population with obesity) and iii) with a new sensory method (a four solutions' ranking task) that preserves automatic configural processing necessary for the OITE to occur.

2. Materials and methods

2.1. Participants

We recruited French participants, 43 with normal-weight (NW: 25 $kg/m^2 <$ body mass index) and 38 with obesity (OB: body mass index $\geq$ 30 kg/m^2). The groups were homogeneous in terms of age, gender, socio-professional statuses and level of study but differed by weight status (NW: mean BMI = 22.2 SD = 1.6, OB group: mean BMI = 37.3 SD = 5.1) (supplementary data: Table 1). The participants were measured and weighed at the end of the first session. They should not eat, drink or smoke at least 1:30 before the sessions. The experimental procedure was explained to each participant before recruitment and before each test session. Participants signed an informed consent form to participate in the study and received compensation for the time spent performing the study. The study was conducted following the Helsinki Declaration and was approved by the CPP EST I #19.04.26 ethics committee (ID RCB #2019-A00120-57).

2.2. Solutions

A series of pre-tests were performed to determine i) bases and aromas choices (pre-test 1), ii) salt and sucrose concentrations for references (pre-test 2). In pre-test 1, expert groups of 3 to 6 participants internal to the CSGA lab evaluated 8 sweet and salty bases and 42 odorants. A set of 17 complex solutions were selected from these preliminary tests. Odorants were chosen for their potential to increase sweetness/saltiness, not being too pungent, long-lasting in the mouth, and not being very unpleasant. The three last criteria were chosen to avoid strong disturbance during the ranking sessions. Pre-test 2 was performed with a panel of 16 participants internal to CSGA to validate the sugar/salt concentrations of the references. The references were built following two

Table 1
Concentration (w/w) of each odorant and taste compound in each base. S1, S2, and S3 represent the three levels of tastants' concentrations used for each ranking task. Aj, Coc and Wsw were prepared with sucrose, and Gp and Wsa were prepared with NaCl.

Beverage base	Odorant	S1	S2	S3	S1 + Odorant
Apple Juice (Aj)	Vanillin	4 %	6 %	8 %	4 % + 0.03 %
	French vanilla	4 %	6 %	8 %	4 % + 0.01 %
	Lychee A&G	4 %	6 %	8 %	4 % + 0.02 %
	Lychee Fir	4 %	6 %	8 %	4 % + 0.02 %
Cocoa (Coc)	Ethyl-vanillin	5 %	9 %	13 %	5 % + 0.040 %
	French vanilla	5 %	9 %	13 %	5 % + 0.006 %
	Furaneol	5 %	9 %	13 %	5 % + 0.015 %
Sweet Water (Wsw)	Vanillin	4 %	7 %	10 %	4 % + 0.06 %
	French vanilla	4 %	7 %	10 %	4 % + 0.01 %
	Ethyl-vanillin	4 %	7 %	10 %	4 % + 0.03 %
	Lychee A&G	4 %	7 %	10 %	4 % + 0.02 %
	Lychee Fir	4 %	7 %	10 %	4 % + 0.02 %
	Furaneol	4 %	7 %	10 %	4 % + 0.01 %
Green-pea soup (Gp)	Bacon	0.25 %	0.50 %	0.75 %	0.25 % + 0.005 %
	Garlic	0.25 %	0.50 %	0.75 %	0.25 % + 0.045 %
Salty Water (Wsa)	Bacon	0.10 %	0.18 %	0.25 %	0.10 % + 0.005 %
	Garlic	0.10 %	0.18 %	0.25 %	0.10 % + 0.025 %

requirements on the intensity levels, which should be i) sufficiently different to allow a precise ranking and ii) sufficiently close to allow a precise ranking of the target solution. In addition, the highest reference concentration was chosen to be close to commercially available products. The lowest reference was chosen as the half of the highest concentration, or lower, but had to be still easily detectable by all participants of the pre-tests. The intermediate reference was the median between the lowest and the highest concentrations. Participants performed 12 rankings with the selected references and part of the solutions with the added odorants. References were correctly ranked by at least 2/3 of the participants, which validated the test. Finally, based on the availability of the products at the moment of the test, 3 complex bases and 8 odorants were selected for the final testing as odor-induced taste enhancers. Concerning the odor-induced **sweetness** enhancement, 3 beverage bases were used: Apple juice (Aj), Cocoa (Coc) and sweet Water (Wsw). The Aj base was constituted of apple juice (Jus de pomme 100 % pur jus Carrefour Extra, Carrefour, France), initially containing 10 % (weight/weight (w/w)) of sugars, which was diluted at 4 % (w/w) with water (Evian, France). The Coc base was prepared by extracting the supernatant after centrifugation (Beckman Coulter, 15,000 RPM, 20 °C, 30 min, acceleration max, deceleration min) of a non-sweetened cocoa powder (Carrefour, France) dissolved in water at 4 % (w/w). The Coc base was prepared by dissolving 5 % (w/w) sucrose (Béghin Say, Tereos, France) in the cocoa supernatant. Sucrose was dissolved in water at 4 %, 7 % and 10 % (w/w) to prepare the Wsw bases. Depending on the base, different odorants were selected. For the Aj base, we selected vanillin (Sigma Aldrich, CAS: 121–33-5), a frenchvanilla odorant composition (Arômes et Liquides, France), two lychee odorants (A&G: Arômes & Gourmandiz, France, and Fir: 502187A, Firmenich, Switzerland). For the Coc base, we selected ethyl-vanillin (Sigma Aldrich, CAS: 121–32-4), a frenchvanilla odorant composition (Arômes et Liquides, France) and furaneol (Dimethy Hydroxy Furanone, 943979, Firmenich, Switzerland, CAS: 3658–77-3). All the odorants tested in both Aj and Coc were also tested in the sweet water-base (concentrations are listed in Table 1).

Two bases were selected to study the odor-induced **saltiness** enhancement: Green-pea soup (Gp) and salty Water (Wsa). The Gp was prepared by extracting the supernatant of an unsalted green-pea puree (Bledina, les récoltes bio, France) through centrifugation (Beckman Coulter, 15,000 RPM, 20 °C, 30 min, acceleration max, deceleration min). To prepare the Gp base, 0.25 % of NaCl (Sigma-Aldrich) was dissolved in the Gp supernatant. A smoky bacon odorant composition (Bacon smoked flexarome, 880,501 FB542, Firmenich, Switzerland) and a smoked garlic odorant water extract (Ducros, France) were chosen as potential saltiness enhancers for both Gp and Wsa. The bacon odorant was dissolved in Gp and Wsa at 0.005 %. We infused the smoked garlic powder in warm Evian water (75 °C, 3 min) at 0.6 % (w/w) and diluted this infusion in Gp and Wsa at 0.045 % and 0.025 % (w/w), respectively.

For the ranking task, three solutions with increasing concentrations of either sucrose or sodium chloride (S1 to S3) were prepared for each base. The fourth solution contained the target odorant diluted in the S1 solution (Table 1).

2.3. Sensory procedure

The rankings were organized in two sessions of 1:30, separated by 6 to 9 days (Fig. 1A). To limit fatigue and optimize the olfactory capacities of the participants, the number of rankings was limited to 10 per session. To equilibrate the two sessions, Aj and Wsw solutions were tested in the first session, and Coc, Gp and Wsa were tested in the second session. The questionnaire and data collection were monitored with Fizz software (Biosystèmes, Couternon, France). Each odorant was tested in a dedicated ranking task (Fig. 1B). The participants received three sweet or salty base solutions (e.g., AjS1, AjS2, and AjS3) and one of the odorant-added solutions (e.g., AjS1 + vanillin); they were asked to rank the 4 bottles from the lowest to the highest sweetness/saltiness intensity. The ranking tasks' and solutions' orders were counterbalanced across participants.

The solutions were delivered using spray bottles, which avoided orthonasal perception before tasting. Participants were first trained to use the spray bottles. To perform the ranking task, the panelist had to deliver two pulses of each solution in the mouth, swallow and rank the bottles accordingly to their salty/sweet intensity; ties were not allowed. They could rinse their mouth with lukewarm Evian© water (40 °C) when necessary. After a preliminary ranking, they were instructed to confirm their choice by testing each solution again, modifying the ranking when necessary, and then registering their ranking on the computer. The subjects had to rinse their mouth with lukewarm water and wait for 30 s. between two ranking tasks. After the ranking task, participants rated the pleasantness of the solutions on an unstructured linear scale from "not pleasant at all" to "very pleasant". Samples were presented in a counterbalanced order. Again, the participants had to rinse their mouth with lukewarm water and wait for 30 s. between samples.

At the end of the second session, the participants filled the French version (Brunault et al., 2015) of the Dutch Eating Behaviour Questionnaire (DEBQ, Strien, Frijters, Bergers, & Defares, 1986). This questionnaire comprises 33 items that characterize eating behaviors personality traits. Three scores were calculated from the 33 items to assess the level of "external eating", "emotional eating," and "restrained eating". Within the emotional eating section, "defined" and "diffused" emotional eating scores were calculated. The participants also completed a French version of a western diet questionnaire adapted from the Dietary Fat and free Sugar – Short Questionnaire (DFS-SQ) developed by Francis and Stevenson (2013). The questionnaire included 26 food items to measure saturated fat and free sugar intake. The participants had to choose how many times they consumed this food during the last month, "less than 1 per month", "2–3 per month", "1–2 per week", "3–4 per week" and "5 + per week". The participants rated their hunger state on an unstructured linear scale from "not hungry at all" to "very hungry", at the begining and the end of each session.

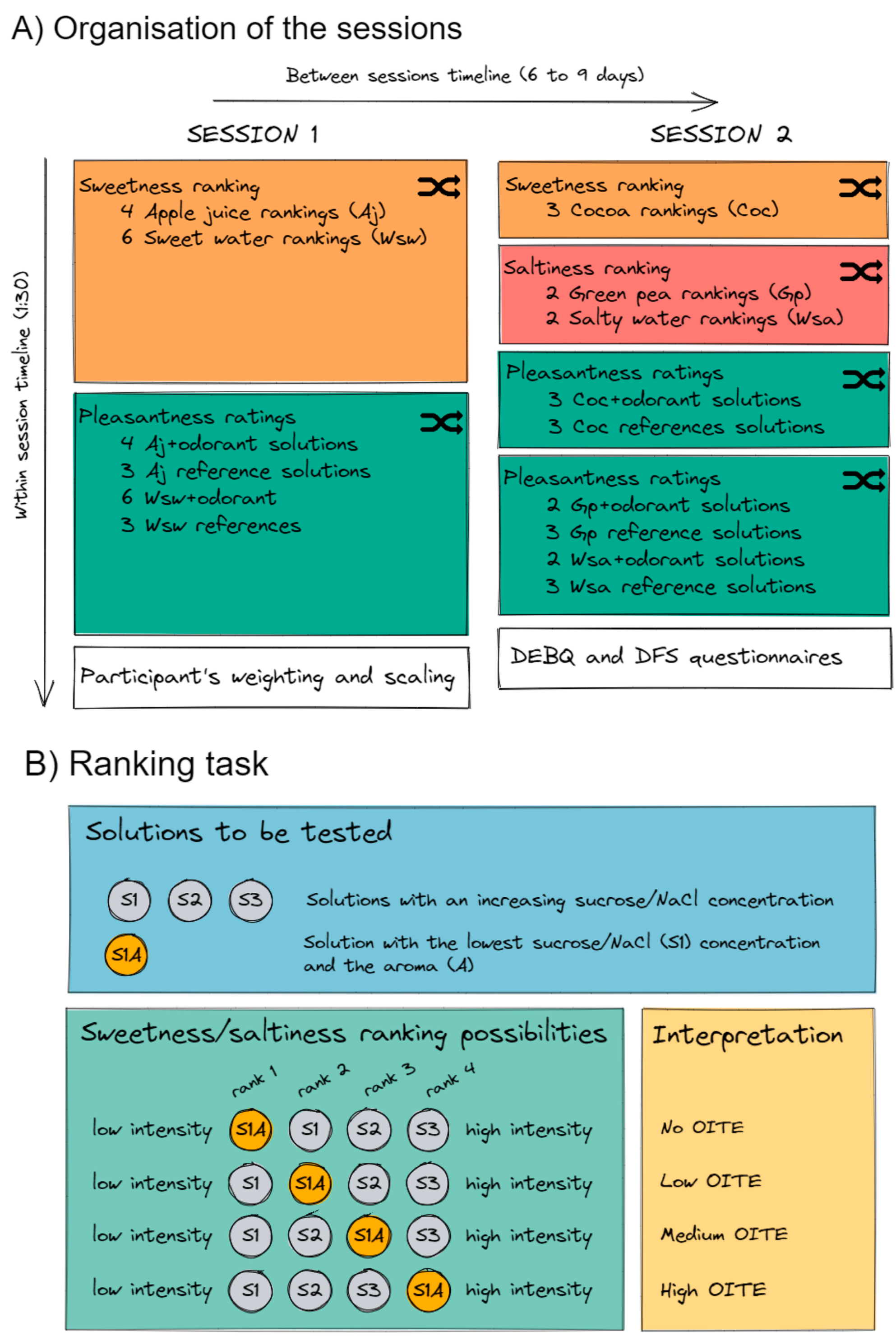

Fig. 1. A) Organisation of the experimental sessions. Timeline of the sessions and within-session organization of the different rankings and tasks. The shuffle symbol indicates that the solutions were counterbalanced across participants within the solutions block. B) Details of the ranking procedure to assess the odor-induced taste enhancement (OITE).

2.4. Data analysis

Data analysis was performed on R 3.5.1 (R Core Team, 2020). For each ranking task, a Wilcoxon test was applied to check whether participants correctly ranked the three salty or sweet solutions without odorants (i.e., S1 < S2 < S3). References were used as an "intensity scale" in the data analysis and as quality control for data inclusion. An incorrect ranking of the references produces an invalid "reference scale" and the accuracy of ranking the OITE solution is unreliable. Therefore, to reduce noise in the data, incorrect rankings of the references were removed (median percent of data excluded was 15 % for NW and 17 % for OB, supplementary material Table 2). A Wilcoxon test was performed to compare the ranking of the sample with the odorant added (S1+A) against the base solutions with the different levels of sugar (or salt) (S1, S2, S3); this comparison was used as a characterization of the OITE (Fig. 1B). OITE levels were defined as no-OITE, low, medium and high

Table 2
Mean scores (standard deviation) of the hunger state and the questionnaires' items by groups.

	NW	OB	Comparison NW vs OB
Hunger state beginning of session 1 (SD)	4.8 (2.88)	3.2 (2.44)	**
Hunger state beginning of session 2 (SD)	4.6 (2.88)	3.2 (2.64)	**
DEBQ restriction score (SD)	2.60 (0.84)	2.90 (0.74)	NS
DEBQ external score (SD)	3.11 (0.46)	2.96 (0.42)	NS
DEBQ emotional score (SD)	2.45 (0.81)	2.51 (0.84)	NS
DEBQ emotional defined score (SD)	2.27 (0.79)	2.38 (0.89)	NS
DEBQ emotional diffused score (SD)	2.96 (1.00)	2.84 (0.90)	NS
DFS-SQ global score (SD)	49.7 (8.5)	46.8 (7.9)	NS
DFS-SQ salty food score (SD)	24.5 (4.7)	23.5 (4.1)	NS
DFS-SQ sweet food score (SD)	25.2 (4.8)	23.3 (5.0)	NS
DFS-SQ beverages score (SD)	8.9 (2.7)	8.7 (2.9)	NS

OITE when the solution with the odorant was positioned at rank 1, 2, 3, or 4, respectively. A Wilcoxon Mann Whitney test was performed to compare the ranking of the odorant-added solution between OB and NW groups, in each base. Wilcoxon tests were corrected with a False Discovery Rate (FDR) for multiple comparisons; and were considered as significant when $p < .05$ (*), $p < .01$ (**), and $p < .001$ (***). To facilitate the understanding, the results were represented in terms of the proportion of participants who ranked the samples in the first, second, third, or fourth position (i.e., distribution of the rankings, Fig. 2). An analysis of variance was performed using a Linear Mixed Effect model (LME) to compare the *pleasantness* of the *solutions* as a function of the *group* with the *participants* as a random factor. Tukey post-hoc tests were performed to compare the different solutions within each group; they were considered significant when $p < .05$ (supplementary material Table 3). A hunger index was calculated by participants and by sessions, by subtracting the hunger state at the end and the beginning of the session. Student t-tests were used to test 1) whether the hunger state changed during the sessions for each group and 2) to compare the hunger state at the beginning of the session between the groups.

For the DEBQ, the average score of personality traits' items was calculated for external eating, emotional eating (defined and diffused) and restrained eating. LME was used to model the different *scores* by *group,* with the *participants* as a random factor. Cronbach's alpha was calculated to evaluate the items' consistency (i.e., variance's homogeneity among the different items of a category) within each category for each group. A value higher than 0.7 indicated the items' consistency within one category. The global score of the DFS-SQ was calculated for each subject, as well as 3 other scores to assess the frequency of consumption of salty foods (questions: Q1:Q12 + Q25), sweet foods (questions: Q13:Q24 + Q26) and sweet beverages (questions: Q20:Q23 + Q26). An LME model was applied to the *score* as a dependant variable, the *group* as an independent variable, and *participants* as a random factor. The tests were considered as significant when $p < .05$.

3. Results

3.1. Hunger Index, DEBQ and DFS-SQ score

Differences of hunger were found between the groups at the begin of each session (session1: $t(78) = 2.71$, $p = .008$; session2: $t(78) = 2.67$, $p = .009$) with an average score of 4.8 for the NW and 3.2 for the OB in session 1 and 4.6 for the NW and 3.2 for the OB in session 2 (Table 2). However, no difference of hunger states between the begin and the end of the sensory session 1 or 2 was found for the NW group (session 1: $t(42) = -1.56$, $p = .12$; session 2: $t(42) = -1.56$, $p = .13$) or the OB group (session 1: $t(36) = -0.75$, $p = .46$; session 2: $t(36) = 0.13$, $p = .90$). Therefore, the hunger state was not a confounding factor that could have modified OITE in the course of the session.

For the DEBQ, no significant difference between the groups was observed on the restrained ($F(1,78) = 2.76$, $p = .10$), external ($F(1,78) = 2.32$, $p = .13$) and emotional eating behaviors ($F(1,78) = 0.11$, $p = .74$). Within the emotional eating behaviors no significant differences were found neither on the emotional defined eating ($F(1,78) = 0.33$, $p = .56$) nor on the emotional diffused eating ($F(1,78) = 0.30$, $p = .58$). The Cronbach alphas were higher than 0.7 for all the categories except for the external score for the NW group (Cr = 0.61) which highlighted differences in the answers for the items within this category for the NW group. For the DFS-SQ, no significant difference between the groups was observed for the global questionnaire ($F(1,78) = 2.45$, $p = .12$), the items corresponding to salty foods ($F(1,78) = 1.08$, $p = .30$), the items corresponding to sweet foods ($F(1,78) = 1.08$, $p = .30$) and the items corresponding to beverages ($F(1,78) = 1.08$, $p = .30$).

3.2. OITE in sweet complex beverages

For a global overview, the statistical results that show OITE have been compiled in Table 3 of the supplementary material.

In the apple juice base, AjS1 + vanillin was ranked significantly higher than AjS1 by OB ($W = 252$, $p = .003$) but not by NW ($W = 316$, $p = .14$). OB experienced OITE in the apple juice but not the NW group. Interestingly, OB perceived AjS1 + vanillin as sweet as AjS2 (as 37 % of participants ranked the solution higher than AjS2, $W = 108$, $p = .22$), which was interpreted as a medium OITE since the perceived sweetness level in the odorant-added solution was as sweet as a juice with 50 % more sugar. The french vanilla produced OITE only in NW, AjS1 + frenchvan was ranked as significantly higher than AjS1 by NW ($W = 462$, $p = .025$) but not by OB ($W = 268.5$, $p = .11$). AjS1 + frenchvan was perceived as less sweet than AjS2 in NW ($W = 54$, $p < .001$), which corresponds to a low OITE. A&G Lychee odorant did not produce OITE in the apple juice base in none of the groups. AjS1 + lycheeA&G was not ranked higher than AjS1 neither in NW ($W = 316$, $p = .14$) nor in OB ($W = 273$, $p = .19$). The lycheeFIR did not produce OITE in apple juice in any of the groups. AjS1 + lycheeFIR was not ranked as significantly higher than AjS1 neither for NW ($W = 326$, $p = .91$) nor for OB ($W = 224$, $p = .34$).

In the cocoa beverage, the frenchvanilla odorant produced OITE in OB but not in NW, CocS1 + frenchvan was ranked as significantly higher than CocS1 by OB ($W = 365.5$, $p = .01$) but not by NW ($W = 480$, $p = .29$). CocS1 + frenchvan was perceived as less sweet than AjS2 in OB ($W = 48.5$, $p < .001$), corresponding to a low OITE. Ethyl-vanillin odorant produced OITE in the cocoa beverage in OB but not in NW, CocS1 + ethvan was ranked as significantly higher than CocS1 by OB ($W = 390.5$, $p = .03$) but not by NW ($W = 314.5$, $p = .53$). CocS1 + ethvan was perceived as less sweet than CocS2 in OB ($W = 49.5$, $p < .001$), corresponding to a low OITE. Finally, the furaneol odorant produced OITE in the cocoa beverage in OB but not in NW group, CocS1 + furaneol was ranked significantly higher than CocS1 in OB ($W = 352$, $p = .02$) but not in NW ($W = 390$, $p = 1$). CocS1 + furaneol was perceived as less sweet than CocS2 for OB ($W = 0$, $p < .001$), corresponding to a low OITE.

3.3. OITE in salty complex beverages

In the green pea soup base, GpS1 + bacon was ranked as significantly higher in saltiness than GpS1 by OB ($W = 287$, $p = .009$) and by NW ($W = 472$, $p = .05$). NW and OB both experienced OITE by the bacon odorant in the green-pea soup. Both groups evaluated the GpS1 + bacon as less salty than GpS2 (OB: $W = 33.5$, $p < .001$; NW: $W = 92$, $p < .001$), corresponding to a low OITE. NW and OB did not rank differently GpS1 + bacon ($W = 286$, $p = .62$). GpS1 + garlic was not ranked as

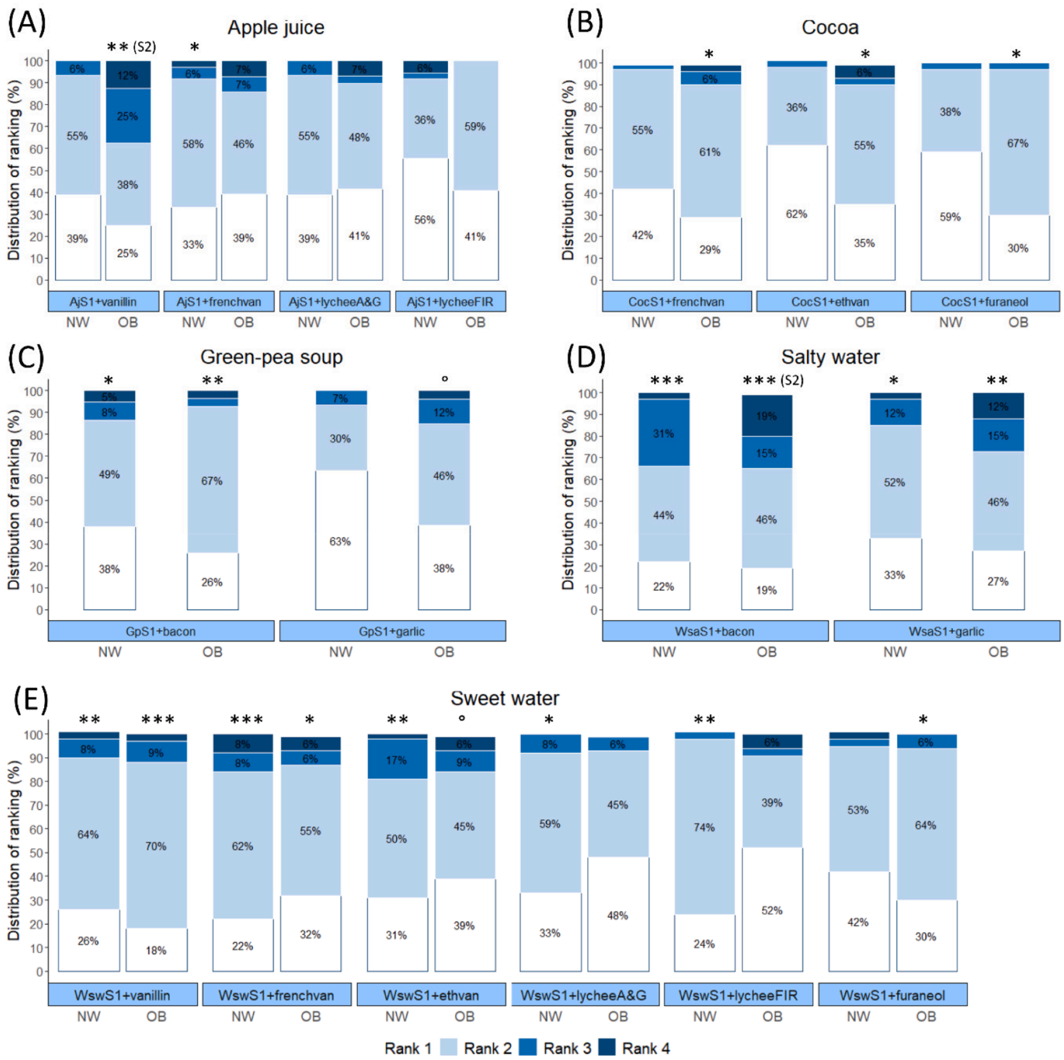

Fig. 2. Distribution of the ranking scores, expressed as proportions of the solutions in A) an apple juice base containing one of the target odorants [vanillin, frenchvanilla (frenchvan), lychee A&G (lycheeA&G), or Firmenich (lycheeFIR)], B) a cocoa beverage with one odorant (frenchvan, ethyl-vanillin (ethvan), or furaneol), C) a green-pea soup with one odorant (bacon, or garlic), D) salty water with one odorant (bacon or garlic), and E) sweet water with one odorant (vanillin, frenchvan, ethvan, lycheeA&G, lycheeFIR or furaneol). The color gradient corresponds to the distribution of the solution in ranks 1, 2, 3, or 4. The stars indicate that the solution S1 is significantly different from the solution containing S1 + odorant at respectively: ***: p <.001; **: p <.01; *: p <.05; °: p ≤ 0.10 (Wilcoxon test). The letters and numbers in brackets indicate that the solution is perceived as sweet/salty as the second (S2) or third (S3) concentration of sugar or salt. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

significantly higher than GpS1neither in NW (W = 189.5, p =.33) nor in OB (W = 236, p =.10). Neither OB nor NW experienced OITE in the green-pea soup with the smoked garlic odorant.

3.4. OITE in sweet water

In the sweet water base, WswS1 + vanillin was ranked as significantly sweeter than WswS1 by OB (W = 471, p <.001) and NW (W = 600, p =.001) (Fig. 2E). Both groups experienced OITE in sweet water with vanillin. Both groups evaluated the WswS1 + vanillin as less sweet than WswS2 (OB: W = 70.5, p <.001; NW: W = 77.5, p <.001), corresponding to a low OITE. Finally, NW and OB did not rank differently WswS1 + vanillin (W = 591.5, p =.48). Similar results were found with the frenchvanilla odorant in sweet water, WswS1 + frenchvanilla was ranked as significantly sweeter than WswS1 by OB (W = 356, p =.02) and NW (W = 662.5, p <.001). Both groups experienced OITE in the sweet water with the frenchvanilla. Both groups evaluated the WswS1 + frenchvan as less sweet than WswS2 (OB: W = 71, p <.001; NW: W = 147, p <.001), corresponding to a low OITE. NW and OB did not rank differently WswS1 + frenchvanilla (W = 223.5, p <.26). WswS1 + ethvan was ranked as significantly sweeter than WswS1 by NW (W = 675.5, p =.003) but not by OB (W = 372.5, p =.08). NW experienced OITE in sweet water with ethyl-vanillin but not OB. Moreover, WswS1 + ethvan was evaluated as less sweet than WswS2 in NW (W = 137, p <.001), corresponding to a low OITE. WswS1 + lycheeAG was ranked as significantly sweeter than WswS1 in NW (W = 539.5, p =.02) but not in OB (W = 305, p =.63). NW experienced OITE in sweet water with lycheeA&G but not OB. Moreover, NW evaluated WswS1 + lycheeAG as less sweet than WswS2 (W = 40.5, p <.001), resulting in a low OITE. WswS1 + lycheeFIR was ranked as significantly sweeter than WswS1 in NW (W = 570, p =.001) but not in OB (W = 297.5, p =.74). NW experienced OITE in sweet water with lycheeFIR odorant but not OB. Moreover, in the NW group, WswS1 + lycheeFIR was evaluated as less sweet than WswS2 (W = 15, p <.001), corresponding to a low OITE. Finally, WswS1 + furaneol was ranked as significantly sweeter than WswS1 in OB (W = 401, p =.02) but not in NW (W = 403.5, p =.22). OB experienced OITE in sweet water with furaneol but not NW. Moreover, in the OB group, WswS1 + furaneol was evaluated as less sweet than

Table 3
Summary of the significant odor-induced taste enhancements (OITE) found in the different bases for the different odorants [vanillin, frenchvanilla (frenchvan), lychee A&G (lycheeA&G), lychee Firmenich (lycheeFIR), ethyl vanillin (ethvan), furaneol (caramel-like odor), bacon and garlic]. Results are reported for normal-weight (NW) and obese (OB) populations. Odorants highlighted in red and bold represent the descriptive differences between NW and OB groups.

Bases	NW	OB
Apple juice	**frenchvan (S1 < OITE < S2)**	**vanillin (OITE = S2)**
Cocoa	No OITE	**frenchvan, ethvan and furaneol (S1 < OITE < S2)**
Green-pea	bacon (S1 < OITE < S2)	bacon and **garlic** (S1 < OITE < S2)
Sweet water	vanillin, frenchvan, ethvan, **lycheeA&G and lycheeFIR** (S1 < OITE < S2)	vanillin, frenchvan, ethvan, and **furaneol** (S1 < OITE < S2)
Salty water	**bacon (S1 < OITE < S2)** and garlic (S1 < OITE < S2)	**bacon (OITE = S2)** and garlic (S1 < OITE < S2)
Number of solutions that produced OITE/total number of solutions tested	**9/17**	**12/17**

WswS2 (W = 55, p <.001), corresponding to a low OITE.

3.5. OITE in salty water

In the salty water base, WsaS1 + bacon was ranked as significantly saltier than WsaS1 in the OB (W = 306, p <.001) and the NW groups (W = 566, p <.001). Both groups perceived OITE in the salty water with the bacon odorant. Interestingly, OB perceived WsaS1 + bacon as sweet as WsaS2 (W = 141.5, p =.38) corresponding to a medium OITE, while NW perceived WsaS1 + bacon as less salty than WsaS2 (W = 186, p =.02) corresponding to a low OITE. However, the group difference was not significant (W = 428.5, p =.55). WsaS1 + garlic was ranked as significantly saltier than WsaS1 by OB (W = 281, p =.008) and NW (W = 401.5, p =.02). Both groups experienced OITE in salty water with the garlic odorants. WsaS1 + garlic was ranked lower than WsaS2 in OB (W = 98.5, p =.04) and NW (W = 71.5, p <.001), corresponding to a low OITE in both groups, and not group difference was found (W = 368, p =.32).

4. Discussion and conclusion

The study aimed to determine odor-induced taste enhancement (OITE) differences between obese (OB) and normal-weight (NW) populations on salty and sweet tastes. We hypothesized that OITE would occur in both the NW and the OB populations for sweet and salty tastes but expected that OB would perceive higher sweet OITE than NW. No strong hypothesis could be formulated on the difference between groups for odor-induced saltiness enhancement due to a lack of data in the literature. Our results showed OITE in both populations; however, as a descriptive result, OB experienced OITE in 12 of the 17 solutions tested, and NP experienced OITE in 9 of the 17 solutions. Moreover, OB showed the highest enhancements (i.e., enhancements that reached the second concentration level, S2) in apple juice with vanilla and salty water with bacon, while the NW group did not experience an enhancement that reached S2 in any of the ranking tasks.

4.1. Comparison of the OITE between NW and OB

Although OITE occurred in both populations, we found that OB generally outperformed NW. We highlighted 12 OITE in OB and 9 OITE in NW on the 17 solutions tested. More specifically, the OB group experienced high enhancements in two solutions: vanilla in apple juice and bacon in salty water. In apple juice, 83 % of the OB participants found the vanillin solution sweeter than the same solution without the odorant. Among this population, 37 % perceived the vanillin-added solution as sweeter than apple juice containing 33 % higher sugar concentration, while only 6 % in the NW group. Therefore, the vanillin allowed reducing the sugar in apple juice by 33 % while maintaining the sweetness perception in at least 1/3 of the OB participants tested. Similar results were found in the salty water, in which 81 % of the OB participants perceived the bacon solution as saltier than the same solution without the odorant. In OB, 19 % of the participants ranked the bacon solution as the most intense among the 4 samples, while only 3 % in NW. However, it should be noted that no statistical difference in enhancement was found between the groups in the salty water with bacon.

This high sweetness enhancement is likely due to a stronger odor–taste association in people with obesity. The associative learning theory of Stevenson and Prescott (Stevenson et al., 1998, 1995) appears as a sound theoretical background to explain these results. Following repeated co-exposures to odorants and tastants, the brain encodes a single unified object (flavor) on top or instead of the odor and taste perceptions. The memorization of a configural object allows recalling the flavor object from a single perception (i.e., the odor) (Stevenson & Boakes, 2004). These effects of exposure have been shown in cross-cultural studies where, for example, the smell of vanilla increased more the perception of sweetness in France, while lemon was more effective in Vietnam (Nguyen, 2000). Vanillin is the most commonly used aroma in the food industry (Banerjee & Chattopadhyay, 2019) and consumers are likely highly exposed to this specific odorant with sugars. Participants from the OB group may have been more exposed to these two components due to their food intake habits (Blundell, Gillett, John, & Gillett, 2001), likely leading to higher consumption of sweet food that contained this odorant.

Finally, the reward system may have a role in odor-induced taste enhancement, and functional differences between the two groups may have contributed to OITE differences. Odors and tastes are integrated into different brain areas, including areas of the reward system (i.e., amygdala, orbitofrontal cortex, anterior cingulate gyrus) (Rolls, 2021; Rolls, Critchley, Verhagen, & Kadohisa, 2010; Stevenson & Prescott, 2014). Because people with obesity present a higher sensitization of the reward system to food cues (Kenny, 2011) and as the reward system is involved in the flavor network (Sinding, Aveline, Brindisi, & Thomas-Danguin, 2022), it may have increased the OITE in OB compared to NW.

Some specificities for certain bases or odorants appeared in each group, although OITEs were relatively low. For example, only OB experienced OITE in cocoa. OITE was found with the three odors tested (i.e., two different vanilla and a caramel odor), although the enhancement was relatively low. Specificities for some odorants were found in each group. For example, only OB experienced OITE with the furaneol odorant (caramel-like odor) in cocoa and water solution. Only NW experienced OITE with the two lychee odorants in sweet water. These between-groups differences in OITE could result from differences in flavor exposures. For example, it was shown that OB had a higher preference for chocolate compared to NW (Stafford & Whittle, 2015). It has to be considered that vanilla and caramel odorants are classically used in chocolate or cocoa-based recipes (Januszewska et al., 2020), which supports the idea of a stronger association between vanilla or caramel odors and sweet taste in chocolate bases, more specifically in OB.

On the contrary, both groups experienced OITE with all the vanilla odorants in the sweet water. It should be noted that OB had only a tendency for OITE with ethyl vanillin. This result may show a generalization of the vanilla-induced sweetness enhancement in simple water base. In contrast, the sweetness enhancement appeared more specific in a complex base, the apple juice (i.e., vanillin in OB and French vanilla in NW). In complex bases, congruency might play an important part as some odorants are congruent with the base while others are not. Congruency was defined by Schiffertstein and Verlegh (1996) as "the extent to which two stimuli are appropriate for combination in a food product". While the typicity of a water base drink is low and therefore allows associations with various odorants, complex bases with high typicities, such as apple juice or cocoa, likely reduce the set of potential congruent odors. Furthermore, in complex solutions, taste-taste and other odor–taste interactions might have occurred and overshadowed the vanilla-induced sweetness enhancement (Keast & Breslin, 2003).

4.2. No effect of pleasantness on OITE

Our results showed no differences in pleasantness between the groups (supplementary material, Fig. 1). Moreover, no difference in liking was found between the solutions in the green-pea soup and the salty water. Participants liked the solution with the highest sucrose concentration in the apple juice, the cocoa beverage, and sweet water. Interestingly, no difference in liking was found between the odorant-added solutions and the reference solution for the cocoa beverage and sweet water. In contrast, in the apple juice, the odorant-added solutions were less appreciated than the reference solutions. Empirically, we would assume that congruency is necessary for OITE to occur. Indeed, incongruent odor–taste may not produce OITE, as incongruent odor–taste have likely not been previously experienced together. This effect was nicely shown in a study where various levels of congruency were tested: from very congruent mixtures (citrus odor with sweet and sour tastes to mimic citrus sodas or chicken odor with salty and umami tastes to mimic chicken broth) to very incongruent ones (reversed odor–taste pairing, e.g., chicken odor with sweet/sour taste) (Fondberg, Lundström, Blöchl, Olsson, & Seubert, 2018). The authors showed that congruency positively correlated with pleasantness; the highest the congruency, the highest the pleasantness. However, the relationship between congruency and OITE and between OITE and pleasantness is not straightforward. The authors showed no correlation between congruency or pleasantness and OITE (Fondberg et al., 2018). This result confirmed pioneered findings of Schifferstein & Verlegh (1996), who showed that while congruency acts as a necessary condition for odor-induced taste enhancement, the degree of congruency is not related to the degree of enhancement. Therefore, our results showing no correlation between OITE and pleasantness align with these previous findings.

4.3. No effects of the eating behavior on OITE

We may suppose that the differences in OITE between the groups were due to differences in diet and, more specifically, food intake. Indeed, obesity is associated with preferences for high energy-dense food (sweet and/or fatty) and likely a thrifty metabolism (Blundell et al., 2001). The DFS-SQ (Diet Fat and Free Sugar Questionnaire) was used to measure the participants' monthly intake of saturated fat and free sugar foods. However, no difference in western diet scores was found between the groups, and this result could not account for different levels of OITE. Stevenson et al. (2016) previously tested whether the OITE was linked to a western diet in participants with various BMI. Participants with a healthy diet experienced cherry-induced sweetness enhancement for low and high concentrations of the cherry odorant. In contrast, participants with an unhealthy diet showed cherry-induced sweetness enhancement only when the aroma concentration was low. These results might suggest that participants with an unhealthy diet were more sensitive to the cherry odor. However, the authors did not find a correlation between the western diet level and the detection threshold of the cherry aroma. These results are therefore still pending explanations, and more studies on the topic might provide new explanations.

Similarly, the DEBQ (Dutch Eating Behavior Questionnaire), which measures atypical eating behaviors, did not show differences in eating behaviors between the groups. This questionnaire has shown in two studies that people with obesity have higher restrained and emotional scores that partly explain their weight status (Cebolla, Barrada, Strien, Oliver, & Baños, 2014; Nagl, Hilbert, Zwaan, Braehler, & Kersting, 2016). It is possible that the OB group tested here was not representative of the population with obesity. The willingness to come to the study has likely selected certain personality traits (e.g., curious, outgoing,…) which are unlikely correlated with atypical eating behaviors such as emotional eating, often accompanied by anxiety and depression (Bruch, 1978; Kaplan & Kaplan, 1957). Furthermore, evaluating the food intake and diet type with questionnaires is extremely difficult. Dedicated researches on this question suggest that habitual food intake in obese individuals is greater than it is usually assumed to be. Food intake is often erratic and dysregulated and, therefore, difficult to evaluate retrospectively (Blundell et al., 2001). The auto-evaluation of eating behaviors with questionnaires is also prone to desirability bias (Oliveira, Correia, & Pinh, 2017). This bias consists in attenuating the negative image of himself by giving answers reflecting a better positive image of himself. Therefore, the results of the food intake and feeding behaviors questionnaires should be taken with caution.

4.4. Conclusion

As the main result, our study revealed that people with obesity experienced odor-induced taste enhancement with high strength for two solutions tested, i.e., vanilla in apple juice and bacon in salted water. In contrast, normal-weight people did not experience the same level of OITE. Interestingly, this result was found in sweet solutions and, for the first time, in salty solutions. We suppose that the level of co-exposure to odors and tastes during life could explain these between-groups differences. Indeed, different exposures to food could lead to different associative learning of odors and tastes, resulting in differential odor-induced taste enhancements. As flavor perception is a non-conscious brain construction, it would be interesting to further understand the OITE phenomenon by investigating the brain mechanisms that underpin odor–taste interactions in NW and OB with different food bases.

CRediT authorship contribution statement

Christopher Aveline: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Cécile Leroy:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology. **Marie-Claude Brindisi:** Methodology, Validation, Writing – review & editing. **Stéphanie Chambaron:** Methodology, Validation, Writing – review & editing. **Thierry Thomas-Danguin:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Supervision, Writing – review & editing. **Charlotte Sinding:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2022.104685.

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