Food Research International 226 (2026) 118074

Contents lists available at ScienceDirect

Food Research International

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

Classifying fat-taste sensitivity with repeated threshold testing and an additive-free emulsion: stability and association with PROP bitterness

Ji-Yun Hong, Seo-Jung Noh, Ji-Yun Yang, Myoung-Ji Kim, Jin-Byung Park, Hye-Seong Lee *

Department of Food Science and Biotechnology, College of Engineering, Ewha Womans University, Seoul 03760, South Korea

ARTICLE INFO

Keywords:
Fat taste sensitivity
Oleic acid detection threshold
Signal detection theory (SDT)
DR A-not A method
Repeated threshold testing
PROP bitterness sensitivity
Learning/practice effects

ABSTRACT

Individual variability in oral sensitivity to non-esterified fatty acids (NEFAs), especially oleic acid, is well documented, yet the influence of repeated testing on threshold-based classification has been underexamined. This study aimed to investigate whether repeated evaluations, accounting for learning effects, alter the grouping of fat-taste sensitivity and how this affects fat-taste sensitivity classification. Oleic acid detection thresholds were measured using a signal–detection–based descending-block Dual-Reminder A-Not A (DR A-Not A) method with an additive-free emulsion across eight visits (four two-visit blocks) in a phenotypically similar sample of healthy young Korean women. Participants were classified as hypo- or hypersensitive relative to a 2.8 mM criterion using either a single baseline or the repeated-visits data. After repeated testing, 13 of 40 participants (~33 %) were reclassified, whereas the remainder retained their original classification—consistent with possible practice/learning effects at the individual level. When classification accounted for these effects, PROP bitterness sensitivity was higher in the hypersensitive group; this association was not evident with single-visit classification. The use of an additive-free emulsion minimized potential confounds in fat-taste assessment. Overall, these findings suggest that brief familiarization or reference anchoring, combined with limited targeted repetition in individuals who show practice-related changes, may yield more stable classifications of fat-taste sensitivity and clearer associations with other individual traits.

1. Introduction

Dietary fat contributes to food liking through texture, viscosity, and flavor, but excessive intake can lead to metabolic diseases, such as heart disease and arteriosclerosis (Rai, 2024; Wali et al., 2020), motivating a precise assessment of human fat-taste perception (Mattes, 2005). Even under minimized olfactory and texture cues, humans can detect the taste of non-esterified fatty acids (NEFAs), supporting a distinct oral modality often termed oleogustus (Haryono et al., 2014; Running et al., 2015; Running & Mattes, 2014). Among long-chain fatty acids, oleic acid is frequently used as a model because of its dietary relevance and tractable chemistry (Suga et al., 2016). Oleic acid is a monounsaturated long-chain fatty acid (18:1 cis-9, n-9) with a melting point of approximately 14 °C (Fig. 1).

At the receptor level, evidence implicates CD36 and free-fatty-acid receptors (e.g., FFAR4/GPR120) in transducing oral fatty acids, although hydrophobicity, aggregation, and potential intracellular signaling mechanisms leave aspects of detection mechanisms for fatty acids unclear (Gaillard & Kinnamon, 2019; Kimura et al., 2019; Sugiyama et al., 2022). Physiochemically, NEFAs exhibit limited aqueous solubility and a tendency to form assemblies (Suga et al., 2016); consequently, delivery in oil-in-water emulsions by dispersing FFAs as the oil phase in a continuous aqueous medium—and the emulsion's integrity (droplet size, interfacial composition, viscosity, dispersion uniformity)—can shape potential receptor interactions and perceived intensity (Costanzo & Hartley, 2025; Heinze et al., 2017). Therefore, recent evidence suggests that oral processing and food matrix composition are critical factors in modulating the perception of fat taste (Costanzo, 2024). Using surfactant/additive-free emulsion systems helps reduce matrix-related confounds during threshold testing by avoiding exogenous flavor or mouthfeel cues (Yang et al., 2025).

Inter-individual differences in fat-taste sensitivity are well documented (Heinze et al., 2015; Running et al., 2013), with participants commonly classified as hypo- or hypersensitive (Stewart et al., 2010; Stewart et al., 2011; Tucker & Mattes, 2013). As summarized in Supplementary Table 1, prior studies have predominantly used three-alternative forced-choice (3-AFC) or triangle procedures with ascending concentration series, sometimes combined with staircase

* Corresponding author.
E-mail address: hlee@ewha.ac.kr (H.-S. Lee).

https://doi.org/10.1016/j.foodres.2025.118074
Received 7 August 2025; Received in revised form 9 December 2025; Accepted 14 December 2025
Available online 15 December 2025
0963-9969/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

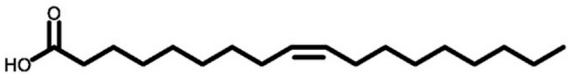


Fig. 1. Structure of oleic acid.

(method-of-reversals) rules to locate detection thresholds (e.g., Tucker & Mattes, 2013; Zhou et al., 2016). These tests have frequently employed milk-based vehicles containing additives (e.g., gum acacia, mineral oil/liquid paraffin, EDTA) and typically relied on single-visit classifications anchored to criterion concentrations around 2.8–3.8 mM. However, most classifications still depend on a single detection threshold, overlooking practice-related learning effects that may arise with repeated exposure to a subtle, unfamiliar quality (Tucker & Mattes, 2013; Keast et al., 2014; Graham et al., 2021a, 2021b; Skoczek-Rubińska et al., 2021). Furthermore, widely used procedures such as ascending 3-AFC or triangle tests estimate sensitivity, but they offer limited ability to separate sensory sensitivity from decision strategy. This can lead to inconsistent classifications across visits, as differences in decision strategy rather than sensory sensitivity may explain variability (Hautus et al., 2011).

Signal Detection Theory (SDT) provides a method-independent sensitivity index (d') and distinguishes sensitivity from decision criterion (β) (Hautus et al., 2021). In sensory decision-making, two major cognitive strategies are recognized: the 'relative' τ-strategy, based on comparison between two or more stimuli, and the 'absolute' β-strategy, which relies on a fixed internal criterion (Lee et al., 2007; O'Mahony and Hautus, 2008; Hautus, van Hout & Lee, 2009; Hautus et al., 2011). Building on SDT and a Thurstonian framework, as illustrated in Fig. 2, the descending-block dual-reminder A-Not A (DR A-Not A) approach presents two reminders of the reference followed by a single blind stimulus (Choi et al., 2023). By providing repeated exposure to the reference, this design facilitates criterion anchoring. It promotes the β-strategy, enabling participants to internalize the sensory characteristics of the reference, thereby reducing cognitive ambiguity and improving test reliability (Kim et al., 2021; Kim et al., 2023; Mun et al., 2019). When combined with controlled, additive-free emulsions, this framework enhances the internal validity of threshold estimation (Yang et al., 2025).

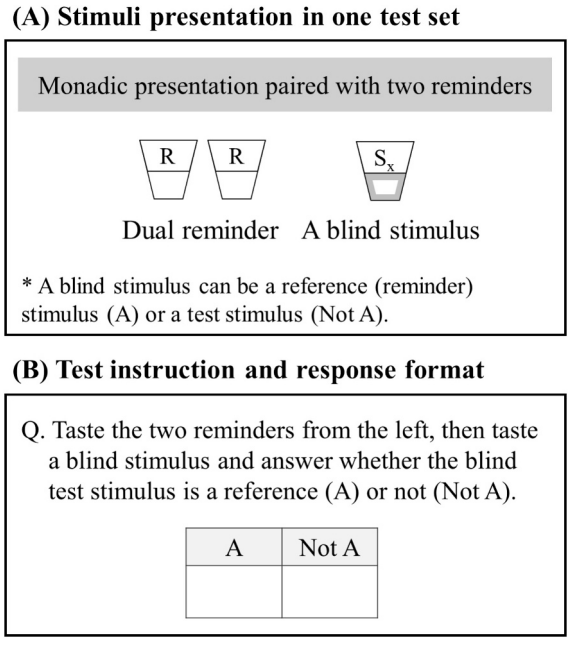


Fig. 2. Design of the dual reminder A-Not A method used for the sensitivity test.

Fat perception may also reflect interactions among multiple taste modalities. 6-n-propyl-2-thiouracil (PROP) sensitivity—one of the most widely studied markers of general oral sensitivity—is mediated by TAS2R38 polymorphisms (Guo & Reed, 2001; Kim et al., 2003). PROP sensitivity has been associated with differences in fat-related sensory experiences (Duffy & Bartoshuk, 2000; Sollai et al., 2019; Tepper & Nurse, 1998), although results are inconsistent across studies (Drewnowski et al., 1998, 2007), potentially due to methodological variation and limited consideration of cognitive factors. To position the present work within this literature and to control for general taste responsiveness, exploratory correlations were therefore examined not only for PROP bitterness but also for two additional bitter tastants (caffeine and quinine) and for sucrose sweetness for a non-bitter comparison. This strategy allows assessment of whether any observed association is specific to PROP or reflects broader taste sensitivity.

In contrast to the conventions summarized in Supplementary Table 1, this study aimed to investigate whether repeated evaluations alter the grouping of oleic acid fat-taste sensitivity. An SDT-based Dual-Reminder A-Not A (DR A-Not A) method with an additive-free emulsion was applied across multiple visits in a phenotypically similar cohort of healthy young Korean women to (i) compare single-visit versus repetition-aware classifications, and (ii) explore potential associations with PROP bitterness sensitivity. Exploratory analyses with caffeine, quinine, and sucrose were included to contextualize any PROP effects. A phenotypically similar sample of healthy young Korean women was intentionally used to limit human-factor variability when evaluating methodological effects; external generalizability should therefore be addressed in follow-up studies (Catherine et al., 2021).

2. Materials and methods

2.1. Subjects and experimental design

For this study, a phenotypically similar group of participants was recruited: Korean young adult women with a normal body mass index (BMI). The World Health Organization (WHO) established a normal BMI range for Asians as 18.5–22.9 (World Health Organization, Regional Office for the Western Pacific, 2000); thus, this range was used to recruit participants. Vegetarians and individuals with taste disorders were also excluded from participating in the experiment. Forty female young adults (age mean ± standard deviation (SD) = 25.0 ± 3.5, BMI mean ± SD = 20.3 ± 1.0) were recruited from the Ewha Womans University online bulletin board in Seoul, South Korea, agreed to the informed consent form for their participation, and completed the whole experiment. The Institutional Review Board Committee of Ewha Womans University accepted this study on ethical and safety grounds (No. ewha-202108-0018-04).

The participants completed two separate phases on different days. During Phase 1, they attended a single session in which the perceived intensities of caffeine, quinine HCl, sucrose, and PROP were evaluated using the general Labeled Magnitude Scale (gLMS). One to three weeks after Phase 1, participants returned for Phase 2 over 8 days, with 1–7 day intervals between visits. Using the descending-block dual reminder A-Not A (DR A-Not A) method proposed by Choi et al. (2023), participants' detection thresholds of oleic acid were evaluated. The overall experimental design is shown in Fig. 3.

2.2. Taste intensity measurement

2.2.1. Stimuli

Four stimuli were used: caffeine (Sigma-Aldrich, St. Louis, MO, United States; Cat. No. C7731), quinine HCl (Sigma-Aldrich, St. Louis, MO, United States; Cat. No. 145920), sucrose (CJ Corp., Incheon, South Korea), and 6-n-propyl-2-thiouracil (Sigma-Aldrich, St. Louis, MO, United States; Cat. No. P3755). Solutions of 3 g/kg (15.45 mM) caffeine, 0.16 g/kg (0.41 mM) quinine HCl, and 200 g/kg (584.29 mM) sucrose

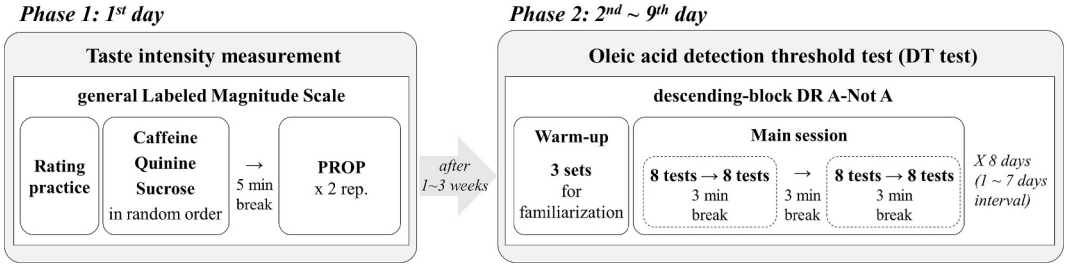


Fig. 3. Overall experimental design. Forty participants completed a 9 day protocol: Day 1 involved taste-intensity measurement, and Days 2–9 included oleic-acid detection threshold (DT) testing across eight visits.

were prepared in low-mineral bottled water (Baeksansu; Nongshim Co., Ltd., Seoul, South Korea). These target concentrations were selected based on previous studies so that the taste stimuli would represent moderate to strong intensity on the gLMS (Bartoshuk et al., 2004; Nolden et al., 2020; Robino et al., 2022). 6-n-propyl-2-thiouracil (PROP) was dissolved in low-mineral bottled water to prepare a 0.54 g/kg (3.2 mM) PROP solution, as described by Tepper and Nurse (1997) and Robino et al. (2022). All stimuli were prepared at least 1 day in advance and stored in the refrigerator at 4 °C. They were served in 10 mL with 3-digit codes in 3-oz. transparent plastic cups to the participants at room temperature (19.5 °C ± 1.4 °C).

2.2.2. Procedure

The participants received instructions on using the gLMS (0, not detectable; 1, barely detectable; 6, weak; 17, moderate; 35, strong; 53, very strong; 100, the strongest imaginable sensation of any kind). To become familiar with the scale anchors, participants were informed that the top of the scale reflected the strongest intensity they could imagine. They were instructed to imagine not only the taste sensations but also all the accompanying sensations, including pain and loudness. As practice for using the gLMS, ratings of the intensity for the brightest light were conducted (Robino et al., 2022). Only when the ratings were lower than "strongest imaginable sensation of any kind" and higher than "very strong", it was concluded that participants used the scale correctly. The procedure for taste intensity measurement followed that of Robino et al. (2022). Caffeine, quinine HCl, and sucrose solutions were presented in random order, and participants were instructed to hold the entire sample in their mouths for 3 s, expectorate, wait 5 s, then rate the intensity of the samples. Following a 5 min break, participants were provided with two PROP solutions, one at a time. To enhance the reliability of PROP sensitivity classification, PROP was presented twice, following Robino et al. (2022). Because bitter taste can linger in the oral cavity, a sufficient rinse interval was included between the two presentations to minimize carryover effects. Participants were instructed to hold the entire sample in their mouths for 10 s, expectorate, wait 20 s, and then evaluate the bitterness intensity. The average of the PROP rating score was used for each participant. After taking each sample, participants washed their mouths with water for 30 s, ate plain crackers for 30 s, and then washed their mouths with water again for 30 s. The evaluation was conducted in the individual sensory booth under the white lights.

2.3. Oleic acid detection threshold test (DT test)

2.3.1. Stimuli

The test stimuli were prepared as oleic-acid oil-in-water emulsions. Briefly, pure oleic acid (CAS No. 112–80–1; Food Chemicals Codex [FCC]; Sigma-Aldrich, St. Louis, MO, United States; Cat. No. W281506) was added to low-mineral bottled water (pH 7.2; Na^+ 10 mg/L; Baeksansu; Nongshim Co., Ltd., Seoul, South Korea) without any added surfactants, emulsifiers, or stabilizers, following the procedure described by Lee et al. (2021). In this study, 'additive-free' refers to the absence of such additives; naturally occurring minerals present in the bottled water (e.g., Na^+ at 10 mg/L) were not modified. The final concentration of the stock emulsion was adjusted to 100 mM.

It was then subjected to homogenization by a horn sonicator (VCX-130, Sonics & Materials, Inc., Newtown, CT, United States; maximum output = 130 W) with a 6 mm (1/4″) stepped microtip. It was sonicated at 70 % amplitude for 10 min using a pulsed mode with 5 s on/off cycles. The fatty acid solutions were homogenized on an ice-water bath to prevent overheating. The low-mineral bottled water was used to dilute the emulsion and also used as the reference stimulus.

For test stimuli (Sx), a 100 mM stock solution of oleic acid was diluted by 0.25 log units, a logarithmic dilution series commonly used in sensory threshold evaluation to prepare the stimulus concentrations. The highest concentration used in this study was 17.73 mM (Step 1), and the step number increased as the stimulus was diluted. To confirm the degree of dispersion of the stock solution, the polydispersity indices (PDI) of all stock solutions prepared for the experiment were measured using dynamic light scattering (nanoSAQLA, Otsuka Electronics Co., Ltd., Hirakata-shi, Osaka, Japan) 1 to 4 days after solution preparation. A PDI value less than 0.25 was considered homogeneous for lipid emulsions (Flores et al., 2011; Pinto et al., 2014). The flow behavior of the reference mineral water and the highest-concentration oleic acid emulsion was characterized using a rotational rheometer (MCR series, Anton Paar GmbH, Graz, Austria) operated with RheoCompass software. At 20 °C, the water reference behaved as a Newtonian fluid with viscosity values around 1.0 millipascal seconds (mPa·s) across shear rates from 1 to 100 s^{-1} (e.g., ~1.0 mPa·s at 50 s^{-1}). The highest-concentration emulsion (oleic acid, 17.7 mM) showed a similarly low, nearly Newtonian profile, with viscosities of approximately 1.1–1.2 mPa·s over the same shear-rate range (e.g., ~1.1 mPa·s near 50 s^{-1}). Thus, even at the highest oleic-acid level, bulk viscosity differed only minimally from water and remained in a water-like range, making salient viscosity-based tactile cues unlikely.

Between 1 and 6 h before the tasting, the stimuli were produced. The dilution procedure to produce various stimulus concentrations followed the sonication of the stock solution. In this study, a wide range of concentrations, from step 1 (17.7 mM) to step 16 (0.31 μM), was prepared for the stimuli. The test stimuli were prepared in a glass wide-neck laboratory bottle with a screw cap to reduce oxidation. Additionally, all stimuli were stored and served at room temperature (23.7 °C ± 0.5 °C). The test stimuli were coded with 3-digit codes, and the reminder (reference, low-mineral bottled water) stimuli were labeled by 'R'. The stimulus was presented in 10 mL in a 4-oz opaque cup with a lid to mask the visual cue. All stimuli were served on a white plastic tray, and the evaluation was conducted under white lights in the individual sensory booth. Participants were asked to wear nose clips to block the olfactory cue. Participants were instructed to taste the stimuli and rinse their mouths between tastings. They were asked to put the whole sample in their mouths, taste it for 5 s, then expectorate it. After tasting the one set, which consisted of the three stimuli, they were required to rinse their mouths with the bottled water and expectorate it.

2.3.2. Procedure

The SDT-based descending block design was used to measure fat-taste sensitivity using oleic acid, as proposed by Choi et al. (2023). In this method, a constant-stimuli approach was employed within each block, where stimuli were presented in a randomized order across the concentration range. This approach was designed to stabilize the decision criterion and improve the reliability of fat-taste sensitivity classification by incorporating repeated exposure to varying concentrations. It allows integration of learning effects and changes across repeated measurements, ensuring that the final thresholds reflect more stable, accurate performance over time. Before the main session, participants completed a warm-up session to become familiar with the task and the sensory characteristics of the stimuli. Each warm-up set contained two stimuli (a reference stimulus and a test stimulus) at three concentrations selected from the six concentrations used in the main test. The lowest, middle, and highest concentrations of the six concentrations used in the main test were selected for the warm-up session. During the warm-up session, participants were informed that the stimuli were the fatty acid emulsion solution. This session was designed to familiarize them with the stimuli in advance and help them recognize the differences between the two stimuli – low-mineral bottled water (reference stimuli) and the fatty acid emulsion (test stimuli).

After the warm-up session, the main test was conducted. Table 1 describes the overall design of the descending-block DR A-Not A method. The main session consisted of 32 sets, divided into two sub-sessions each day. Within each sub-session, participants completed 16 sets organized as two sequences of eight sets each. After the first 8 sets, a 3 min break was given before continuing with the remaining eight sets. In each test set, three stimuli were presented sequentially: the first two were reminder stimuli, and the third was a single blind stimulus. Participants were asked to indicate whether the last stimulus was the same as the reference ("A") or different ("Not A"). The stimulus presentation probability of the reference (R) relative to the test stimuli (Sx) was 1:3, meaning that the reference stimuli were presented 8 times and the test stimuli 24 times per visit. Six concentration steps of oleic acid stimuli were provided as test stimuli, with each concentration step being presented four times per visit. To more efficiently facilitate participants' learning of the differences between the stimuli, the first sub-session presented the three higher concentrations. In contrast, the second sub-session presented the three lower concentrations.

In this method, one block of stimuli corresponded to two successive visits (e.g., Visits 1–2, 3–4, 5–6, and 7–8). The response from the two consecutive visits was used to determine the criterion concentration (S_c). Across the experiment, four criterion concentrations were obtained, and the final S_c from the last visit was used as the individual threshold. Therefore, the fourth-determined concentration served as the threshold throughout the 8 visits in the present study.

The criterion concentration was defined as the highest step at which the lower limit of the 50 % confidence interval of d' of stimuli consecutively indicated 0.5 or higher. In the next visit set, participants were given a block of six stimuli, including one step below the previously determined concentration criterion. This resulted in a gradual decrease in concentrations across visits. If all lower limits of the 50 % confidence interval of stimuli were lower than 0.5, the criterion concentration was determined as the lowest step presented, and an identical block of stimuli was provided in the next visit set. At the last visit set (visits 7–8), the concentration criterion was set to the individual detection threshold for oleic acid. The process for determining a threshold is illustrated in Fig. 4. In the first visit set (visits 1–2), participants began evaluating a block of stimuli from Step 1 (S_1, 17.7 mM) to Step 6 (S_6, 1.0 mM). Once the sensitivity criterion (Sc) was determined from two visits, the subsequent visit began one step lower (i.e., one concentration higher) than the previously identified threshold. This ensured that the next test series always included the concentration surrounding the prior threshold step, maintaining continuity and precision in threshold estimation across visits.

Table 1
Experimental design of the descending-block Dual Reminder A-Not A (DR A-Not A) method.

Stimuli presentation probability[1]	Number of test stimuli presented per day	Number of test sets presented in the main session[2]	
		1st sub-session	2nd sub-session
R:S_x = 1:3	6	16 ① < R – R – R >: 4, ② < R – R – S_1 >: 4, ③ < R – R – S_2 >: 4, ④ < R – R – S_3 >: 4	16 ① < R – R – R >: 4, ② < R – R – S_4 >: 4, ③ < R – R – S_5 >: 4, ④ < R – R – S_6 >: 4

[1] 'R' indicates the reference stimulus and 'S_x' indicates the test stimuli at each threshold step.

[2] As an example, Day 1 consisted of two sub-sessions: three higher-concentration stimuli in the first sub-session, and three lower-concentration stimuli in the second sub-session.

2.4. Statistical analysis

For the descending-block DR A-Not A method, the d' estimates and their 50 % confidence intervals were calculated using the SDT Assistant program (Version 2.0) (Hautus, 2021), assuming the β-strategy model (Choi et al., 2023; Kim et al., 2021; Mun et al., 2019). Response to pair < S_0-S_x > and < S_0-S_0 > was considered as a noise distribution and a signal plus noise distribution, respectively.

Since the distribution of the data is not normal, non-parametric statistical methods were employed. The detection threshold steps for oleic acid were presented as medians and semi-interquartile ranges (SIQRs).

The Wilcoxon signed-rank test was used to assess significant differences in the obtained thresholds across visits. To compare the median threshold steps and intensity ratings of tastes between the groups, the Mann-Whitney *U* test was applied. The Kruskal-Wallis test and Levene's test were used to investigate differences in the averages and variances of intensity ratings for tastes, respectively. All analyses were conducted using XLSTAT (Version 2019.3, Addinsoft, Paris, France).

3. Results and discussion

3.1. Characterization of oleic acid emulsion

To characterize the stock oleic acid emulsion, dynamic light scattering (DLS) analysis was performed across the dilution series prepared as described in Methods (Table 2). At Step 1 (17.7 mM), the mean hydrodynamic diameter was ~249 nm with PDI 0.185 (Table 2). Particle size remained <288 nm down to 1.8 mM (Step 5) in low-mineral bottled water. At ≥0.31 mM (Step 8), PDI values indicated monodispersity (PDI < 0.25; Fig. 5). Oleic acid is known to form liposomal assemblies ~250 nm near neutral pH, with salts (e.g., Na^+) facilitating stabilization (Ferreira et al., 2006; Suga et al., 2016). Taken together, the present emulsions were consistent with homogeneous liposomal dispersions at ≥0.31 mM (Step 8).

Costanzo and Hartley (2025) reported larger, less stable droplets for 2–10 mM oleic acid prepared in filtered water (608–675 nm, with a range of 533–1439 nm during storage). In contrast, our low-mineral bottled-water emulsions showed smaller sizes and lower PDI at comparable concentrations (Table 2). Differences in pH and ionic strength—factors known to shape NEFA self-assembly—likely contribute to these discrepancies (Ferreira et al., 2006; Suga et al., 2016), underscoring the importance of preparation conditions when investigating fat perception.

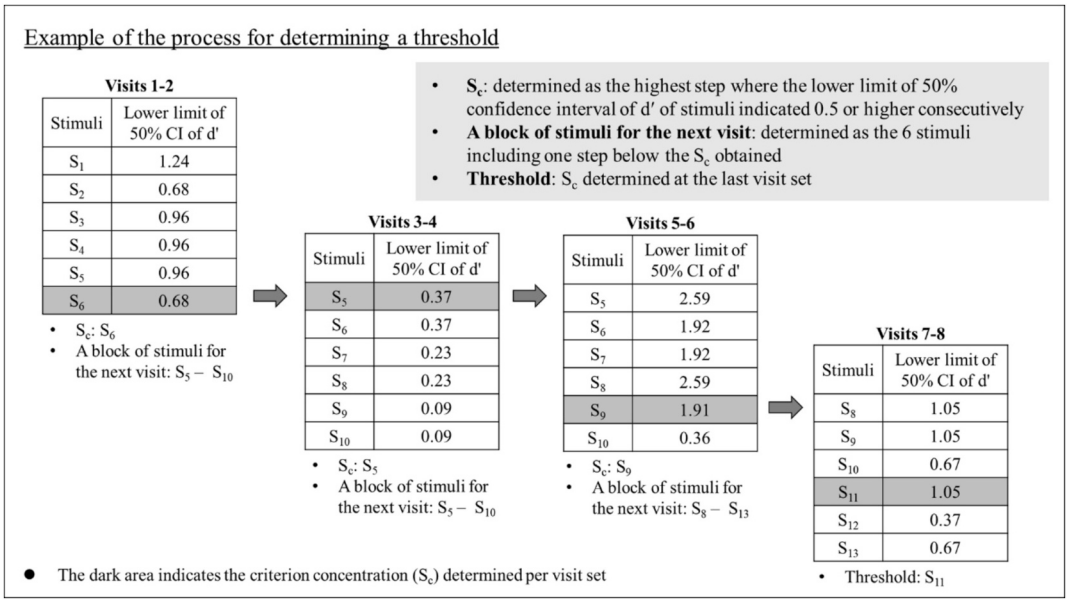


Fig. 4. Example procedure for determining an individual threshold using the descending-block DR A-Not A method over eight visits. [1)] For each stimulus, the lower bound of the 50 % confidence interval (CI) for the d' estimate is computed by pooling responses to 24 blind stimuli—16 for the reference (low-mineral bottled water) and 8 for each test stimulus—across two successive visits (i.e., Visits 1–2, 3–4, …). [2)] S_c denotes the criterion concentration, which exceeds the individual's estimated threshold.

Table 2
Particle size and polydispersity index (PDI) of oleic-acid emulsions used as test stimuli.

Threshold step	Concentration (mM)	Particle size (nm) [1]	Polydispersity Index (PDI) [1]
Step 0 [2]	100	359.500 ± 1.900	0.217 ± 0.026
Step 1	17.7	249.100 ± 3.900	0.185 ± 0.004
Step 2	10.0	242.800 ± 4.100	0.184 ± 0.047
Step 3	5.6	237.100 ± 5.600	0.158 ± 0.030
Step 4	3.1	243.300 ± 7.100	0.182 ± 0.005
Step 5	1.8	287.800 ± 13.400	0.147 ± 0.104
Step 6	1.0	306.500 ± 3.100	0.103 ± 0.031
Step 7	5.6×10^{-1}	310.300 ± 13.400	0.182 ± 0.018
Step 8	3.1×10^{-1}	324.200 ± 1.900	0.215 ± 0.030
Step 9	1.8×10^{-1}	344.500 ± 9.600	0.204 ± 0.017
Step 10	1.0×10^{-1}	473.500 ± 11.700	0.293 ± 0.011
Step 11	5.6×10^{-2}	464.900 ± 23.400	0.246 ± 0.017
Step 12	3.1×10^{-2}	594.200 ± 28.000	0.242 ± 0.028
Step 13	1.8×10^{-2}	634.100 ± 18.100	0.262 ± 0.010
Step 14	9.9×10^{-3}	698.200 ± 54.400	0.373 ± 0.038
Step 15	5.5×10^{-3}	882.000 ± 89.800	0.462 ± 0.061
Step 16	3.1×10^{-3}	994.500 ± 68.500	0.545 ± 0.039

[1] Particle sizes and PDI value represented as mean ± standard deviation (SD).
[2] Step 0 (100 mM) was included for size characterization only and was not included in the detection-threshold test presentations.

3.2. Measuring the detection threshold (DT) of oleic acid

DTs were measured across eight visits using a starting concentration of 17.7 mM, arranged in descending blocks. Learning-related shifts were evident across visit sets (Fig. 6). The maximum concentration detectable by more than half of the participants was 10.0 mM (Step 2) in the first visit set, but 1.8 mM (Step 5) in the last visit set. The median threshold decreased from Step 2 [InterQuartile Range, IQR 1–3] at visits 1–2 to Step 5 [4–6] at visits 7–8 (all pairwise $p < 0.05$; Supplementary Fig. 1); overall range was Step 1 (17.7 mM)–Step 14 (0.99 μM). These shifts are consistent with practice-related gains in a subset of participants. This trend supports prior observations by Heinze et al. (2017), who reported significant threshold reductions across three sessions for oleic acid stimuli, highlighting perceptual and cognitive adaptation over time.

Individual trajectories by group are shown in Fig. 7. Group 1 maintained high thresholds across visits; Group 2 improved; Group 3 was sensitive from the first visit. Group-level medians at visits 1–2 and 7–8 are summarized in Fig. 8. Participants were dichotomized using Step 5 (1.8 mM)—the concentration detected by >50 % at visits 7–8—yielding hyposensitive (undetected at Step 5) and hypersensitive (detected at Step 5) groups. This boundary is close to the ~2.8 mM criterion used by Asano et al. (2016) in a comparable East-Asian cohort.

Initial classification (visits 1–2) yielded 32 hyposensitive and 8 hypersensitive participants. With repetition (visits 7–8), 19 participants remained in the hyposensitive group. In comparison, 21 participants (including 13 reclassified participants) were categorized as hypersensitive (Fig. 8). Group 2 (reclassified) showed significant improvement in threshold step over visits ($p < 0.05$), whereas Groups 1 and 3 did not. Reclassification occurred in 13 out of 40 cases (33 %); the remaining 67 % retained their initial classification. Although 3 participants showed a decrease in fat taste sensitivity across visits, they maintained the same classification.

Prior work similarly reports within-subject variability and practice-related gains in fat-taste thresholds (Newman & Keast, 2013; Running et al., 2013), underscoring the value of repeated assessments with controlled emulsions. These observations highlight the potential impact of perceptual learning, which has been insufficiently addressed in prior literature. Detecting non-esterified fatty acids (NEFAs) is inherently challenging due to their unfamiliarity, lack of clear sensory descriptors, and methodological issues such as emulsification, often resulting in unstable thresholds and practice-related improvements in performance (Running et al., 2013). Consequently, repeated exposure can be important for achieving stable performance and reducing variability, particularly for individuals who initially struggle to detect NEFAs. In the present data, repetition reduced misclassification and yielded more reliable groupings, supporting the view that perceptual familiarization contributes to the stabilization of fat-taste sensitivity.

Building on these insights, the present study incorporated repeated testing with the additive-free emulsion and observed that sensitivity classifications could shift substantially when learning effects were taken into account. This finding highlights the importance of repeated testing to improve reliability and accurately capture individual differences in

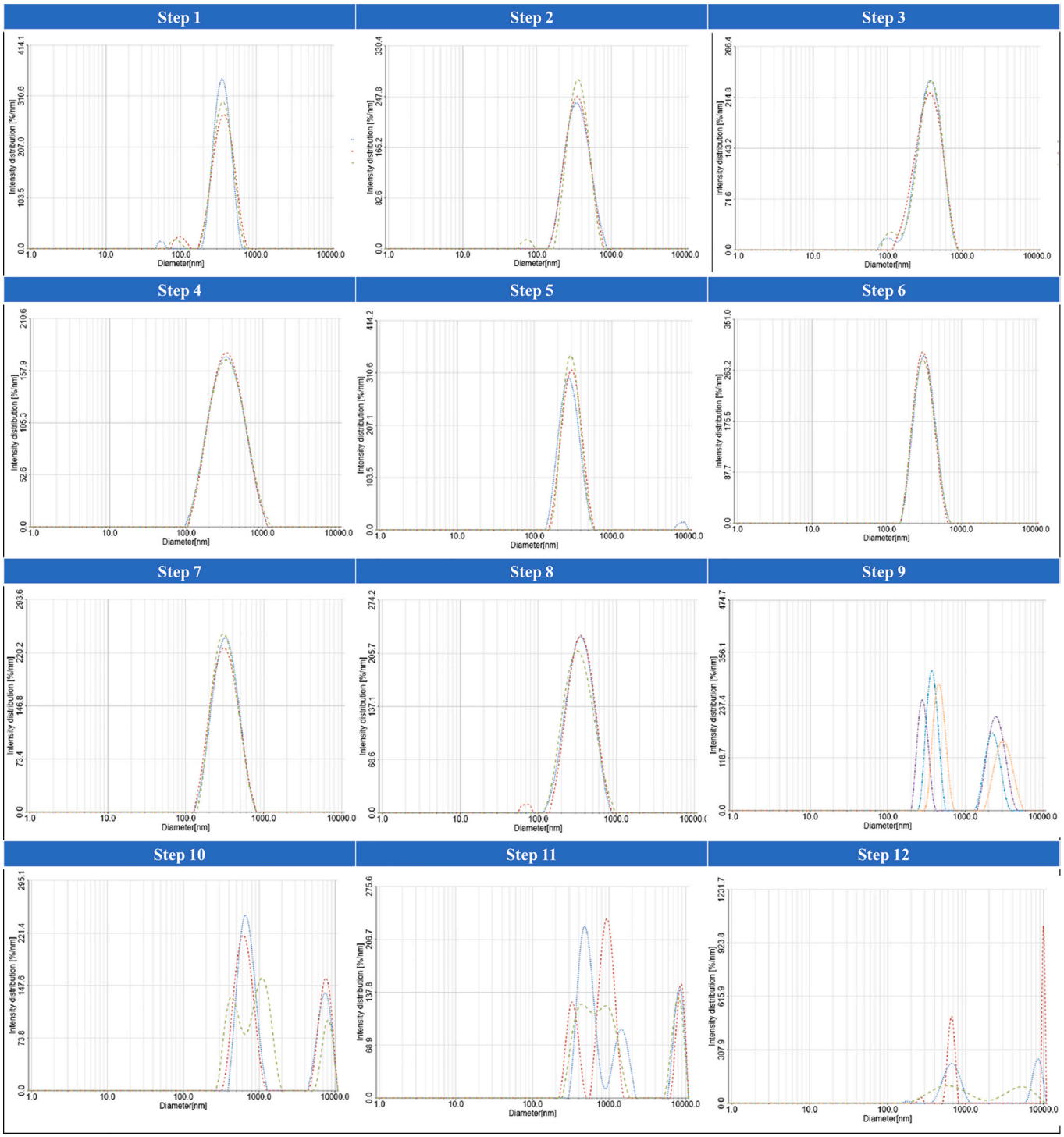


Fig. 5. Dynamic light scattering (DLS) analysis of the oleic-acid emulsion samples; experimental protocols are detailed in the materials and methods section.

fat sensitivity by minimizing misclassification due to transient adaptation or inexperience.

In the present study, several participants changed their sensitivity classification after repeated testing, suggesting that what appears to be "low sensitivity" in single assessments may in fact reflect inexperience rather than a biological limitation. These findings reinforce the notion that perceptual learning constitutes a critical source of within-subject variability in fat-taste sensitivity assessment and must be taken into account to ensure the valid interpretation of individual differences in sensitivity. This indicates that individual differences in learning patterns should be considered in evaluating fat sensitivity.

In our previous comparison of the ascending triangle and descending-block DR A-Not A methods (Choi et al., 2023), repeated testing revealed significant between-person differences in learning, including cases that improved from 101.1 mM to 9.9×10^{-4} mM. Because triangle tests can invite both τ- and β-strategies (Lee & O'Mahony, 2007; Hautus et al., 2021), strategy heterogeneity may amplify variability.

Therefore, in the present study, a descending-block DR A-Not A design was adopted to minimize inter-individual variability in repeated threshold measurements. The descending order allowed participants first to experience stronger stimuli at the beginning of the session,

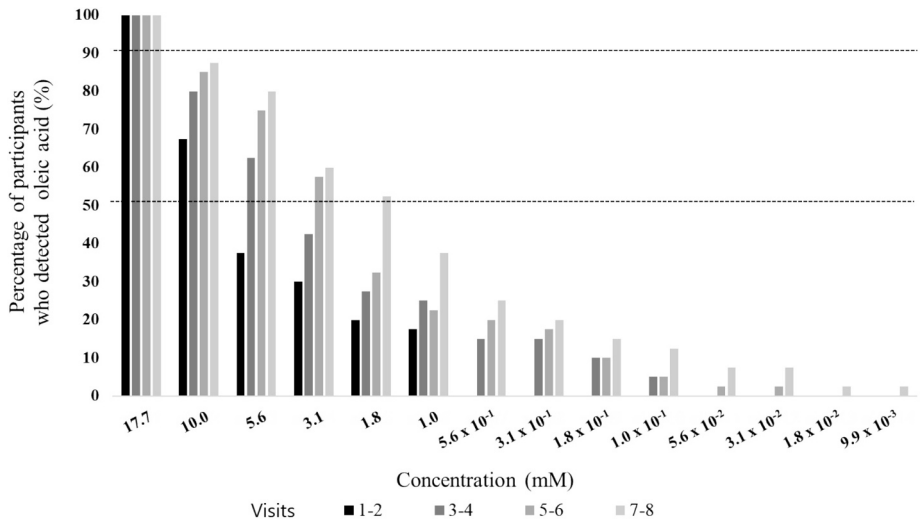


Fig. 6. Cumulative distribution of oleic-acid detection thresholds: the median threshold was 10.0 mM in visit 1–2, whereas 1.8 mM in visit 7–8.

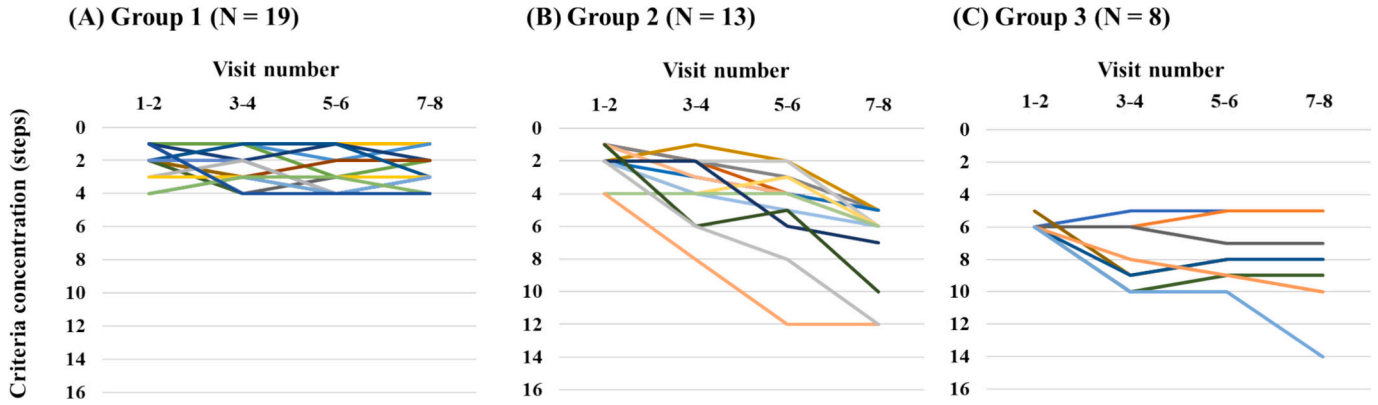


Fig. 7. Individual concentration-step results across visits. (A) Group 1 ($N = 19$): Individuals with no evidence of practice effects across repeated sessions; (B) Group 2 ($N = 13$): Individuals initially insensitive who showed practice-related improvement over repeated sessions; (C) Group 3 ($N = 8$): Individuals sensitive from the first visit.

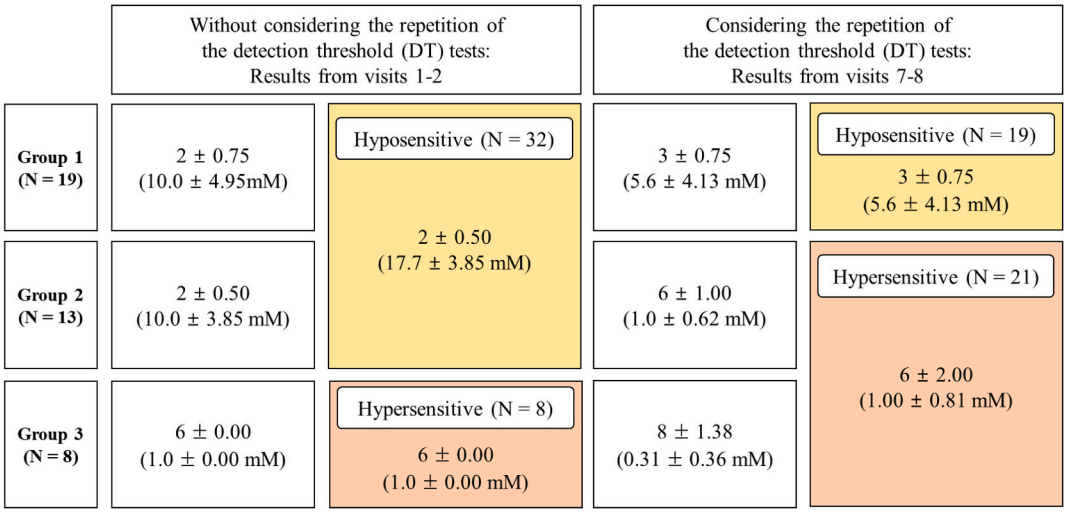


Fig. 8. Median threshold step and corresponding concentration for each group, compared both with and without repetition considered. When repetition was considered, Group 2—initially classified as hyposensitive—was reclassified as hypersensitive.

thereby priming the perceptual system and facilitating the formation of an internal sensory template for oleic acid. As the concentration decreased, participants could match these weaker stimuli against the established template more effectively, improving discrimination at near-threshold levels. This approach, combined with a warm-up procedure and SDT-based d' analysis, enabled more stable threshold estimation by reducing random guessing and enhancing sensitivity consistency across visits. Additionally, thorough rinsing and sufficient inter-trial intervals were implemented to prevent potential coating or carry-over effects from high oleic acid concentrations.

Building on the foundational framework established by Yang et al. (2025), the present study advanced the methodological approach to assessing fat taste sensitivity by isolating the effect of repeated exposure and simplifying the emulsion matrix to exclude potential confounding factors. Yang et al. (2025) applied a modified DR A-Not A method using a food-matrix-based emulsion stabilized with milk proteins to examine the effects of fat type (FFA, TAG, and their mixture) and physicochemical properties on perception; however, group classification was based solely on a single final threshold measurement. In contrast, the present study investigated the perception of an oleic acid emulsion prepared with low-mineral bottled water without any additives. This may allow for minimizing the influence of matrix components and enable a more controlled examination of the effects of repeated testing on DT. By applying an individualized repeated-measures design, we demonstrated that repeated testing not only improved sensitivity classification but also revealed learning-dependent modulation of oral fat perception—an aspect not fully addressed in the previous study. Similarly, Costanzo et al. (2025) developed a simplified lecithin-based emulsion to improve emulsion stability and minimize sensory noise in fat taste threshold testing. However, their study focused solely on comparing emulsion types using the 3-AFC method, without accounting for individual learning effects or incorporating repeated visits. In contrast, the present study combined a surfactant-free emulsion system with an SDT-based DR A-Not A method across repeated measurements, offering a framework for isolating perceptual learning and improving classification accuracy.

Our findings confirm that hypersensitive individuals consistently showed lower DTs across visits, highlighting the role of perceptual learning—an aspect often overlooked in previous research. Overall, by refining the emulsion system and incorporating repeated testing, the present study not only addresses methodological limitations in earlier work but also provides additional evidence for the dynamic and modifiable nature of oral fat perception. These advancements strengthen the basis for exploring how gustatory mechanisms and emulsion structures influence the perception of fat taste.

However, while repeated testing enhances measurement stability, it also raises an important question regarding the nature of the observed improvement—whether it represents an actual change in biological sensitivity or a gain in task-specific perceptual competence. Our findings suggest that the improved detection of oleic acid across visits primarily reflects perceptual and decisional learning rather than a change in innate biological sensitivity. Repeated exposure with dual reminders likely stabilizes the internal decision criterion (β-strategy) and refines a stimulus template for the faint sensory characteristics of NEFAs. The descending-block structure may further facilitate this process, as early exposure to higher concentrations primes the perceptual template, improving recognition at lower concentrations. In parallel, procedural familiarity reduces performance variance (Benjamin et al., 2013; Turner et al., 2011). Similar to the "warm-up" effect described by Angulo et al. (2007), repeated exposure may homogenize individual differences in sensitivity and reduce overdispersion, leading to more stable performance across visits.

3.3. Intensity ratings of tastants

To examine relationships between fat-taste sensitivity and other taste modalities, gLMS intensity ratings (and not thresholds) were obtained for caffeine, quinine, PROP, and sucrose. As summarized in Table 3, mean gLMS intensity ratings across all 40 participants were highest for PROP and lowest for caffeine, with overall differences in intensity among tastants. Although concentrations were chosen to target moderate–strong intensity on the gLMS (Bartoshuk et al., 2004), the perceived intensities were not closely matched; quinine tended to elicit higher mean ratings than caffeine despite targeting the same range. Variability was also greater for quinine and PROP than for sucrose or caffeine, indicating larger inter-individual differences in intensity perception for quinine and PROP.

To test whether general taste responsiveness differed by fat-taste sensitivity group, gLMS intensity ratings of caffeine, quinine, PROP, and sucrose were compared between fat-hyposensitive and fat-hypersensitive groups (Table 4). Without considering repetition (Visits 1–2), no group differences were detected. With repetition (Visits 7–8), PROP intensity ratings were higher in the fat-hypersensitive group than in the hyposensitive group ($p = 0.035$, Mann–Whitney U test). In contrast, caffeine, quinine, and sucrose did not differ. This pattern aligns with reports (e.g., Costanzo, Russell, Lewin and Keast, 2020) that PROP sensitivity can relate to fat responsiveness under controlled emulsion conditions, while acknowledging that prior findings are mixed (Drewnowski et al., 1998, 2007).

These results also indicate that the four tastants were not intensity-matched (e.g., quinine showed both a higher mean and greater variance than caffeine). For future cross-modal comparisons, re-titrating concentrations to achieve closer intensity matching is recommended to reduce within-subject variance. Repetition-aware grouping revealed a PROP difference that was not apparent under single-visit classification.

Taken together, these findings argue for a more targeted and efficient approach to future threshold protocols. For classifying individuals into hyper- versus hyposensitive groups, it may not be necessary to repeat a full descending (or ascending) series across many visits. Instead, a constant-stimuli design could be constructed around a single mid-range "decision block" that spans the concentration range where group separation occurs (e.g., Steps 3–7 in the present data), preceded by a brief warm-up set to familiarize participants with the task and reference. Repeated evaluation within this focused block, implemented within a single session or a short two-session protocol, may be sufficient to obtain stable SDT-based sensitivity estimates for classification. Conversely, when the primary goal is to estimate biological detection or recognition thresholds rather than classify sensitivity groups, future protocols could center a block of constant stimuli on the population's average threshold range and extend testing to higher or lower concentration blocks only if an individual's performance falls entirely above or below that range. Such block-wise, decision-region–focused designs offer a practical means to incorporate learning and familiarity while reducing overall test burden.

3.4. Limitations of the present study

This study has several limitations that should be considered when interpreting its findings, particularly regarding sample composition,

Table 3
Mean and standard deviation (SD) of intensity ratings for each tastant ($N = 40$).

Tastant	Mean ± SD [1, 2]
Caffeine	$24.21 \pm 17.61^{a, A}$
Sucrose	$33.71 \pm 18.36^{ab, A}$
Quinine HCl	$36.34 \pm 19.98^{b, AB}$
6-n-propyl-2-thiouracil (PROP)	$41.69 \pm 28.76^{b, B}$

[1] Within a column, means with different lower-case superscripts differ significantly (Kruskal-Wallis test, $p < 0.05$).
[2] Within a column, variances with different upper-case superscripts differ significantly (Levene's test, $p < 0.05$).

Table 4
Comparison of mean intensity ratings and standard deviation (SD) between hypersensitive and hyposensitive groups, with and without considering repetition.

Tastant	Without considering repetition			Considering repetition		
	Mean ± SD			Mean ± SD		
	Hypersensitive (N = 8)	Hyposensitive (*N* = 32)	*p*-value [1]	Hypersensitive (*N* = 21)	Hyposensitive (N = 19)	*p*-value [1]
Caffeine	22.25 ± 14.68	24.70 ± 18.45	0.598	23.05 ± 14.83	25.50 ± 20.60	0.538
Quinine HCl	36.25 ± 13.45	36.36 ± 21.48	0.456	37.07 ± 18.88	35.53 ± 21.62	0.352
Sucrose	27.69 ± 12.18	35.22 ± 19.46	0.831	36.10 ± 21.44	31.08 ± 14.33	0.342
PROP	34.94 ± 25.55	43.38 ± 29.64	0.710	**49.88 ± 30.61**	**32.63 ± 24.22**	**0.035**

[1] Bold indicates significant difference between the groups (Mann-Whitney *U* test, $p < 0.05$).

methodology, and potential sources of bias. First, the sample consisted solely of healthy young Korean females, limiting the generalizability of the findings to other populations with different genders, ages, ethnicities, or health statuses. Future studies should include diverse demographic groups to improve the external validity of the results. Second, while repeated testing revealed practice-related improvements in some participants, the study design cannot entirely separate perceptual learning from other potential sources of intra-individual variability, such as menstrual cycle-related hormonal fluctuations or chronobiological factors. Future studies may benefit from controlling for these factors. Emerging evidence suggests that taste sensitivity can fluctuate throughout the menstrual cycle (Costanzo, 2024), indicating that some of the observed changes in fat-taste detection thresholds might be influenced by chronobiological factors rather than solely by learning effects. Given that all participants were young, healthy females, this potential confound cannot be ruled out. Future studies should include more diverse participant groups to assess whether these findings are consistent across different demographic and health profiles. Third, the absence of complementary physiological or biological measures, such as fungiform papillae density, genetic markers (e.g., TAS2R38, CD36 variants), or dietary fat intake, limits the ability to distinguish biological sensitivity from performance-based changes across visits. Incorporating these measures in future research would enable better differentiation between biological thresholds and learning-related effects.

Methodologically, this study employed an SDT-based descending-block DR A-Not A design, combined with a constant stimuli approach across the entire concentration range, spanning four two-visit blocks. This method enabled repeated assessments and ensured reliable classification of fat-taste sensitivity. Repeated measurements were used to stabilize the decision criterion and improve classification reliability, thus minimizing the impact of learning-related effects and enhancing the accuracy of sensitivity classification over time. Consequently, the present data do not reveal how threshold estimates or learning patterns might differ when an ascending procedure or more efficient limited-repeat protocols are used. Future studies should focus on repetition in mid-range decision regions, for example, by using a constant-stimuli block targeting the concentrations separating hypo- and hypersensitive groups (e.g., Steps 3–7), preceded by a brief warm-up set. Direct comparisons of ascending and descending series, along with decision-region–focused constant-stimuli designs, could help clarify hysteresis effects and assess how procedural direction, oral residue, fatigue, and block structure influence the stability of threshold classification. Although viscosity measurements confirmed that all stimuli remained within a low, water-like viscosity range and were statistically indistinguishable from the reference, subtle tactile contributions cannot be entirely excluded. Future studies should consider measuring tactile responses to clarify this aspect further.

The final detection thresholds obtained in this study should be interpreted as learning-stabilized perceptual sensitivity, rather than pure innate sensitivity, reflecting the combined effects of learning and repeated exposure. Future studies should differentiate between biological thresholds and performance-based measures by incorporating neurophysiological and genetic correlations alongside behavioral data to provide a more comprehensive understanding of fat-taste sensitivity. In this context, limited, strategically targeted repetition—either by repeatedly sampling a single decision block for classification or by centering a block on the average threshold range and extending testing only to higher or lower blocks when necessary—may not only improve reliability but also help accurately capture perceptual competence in fat-taste sensitivity measurement, particularly for individuals showing substantial within-subject variability.

To improve emulsion stability and ensure consistent fatty acid delivery, future studies should focus on optimizing the pH and salt concentration of the emulsion. While mineral water was used as a base in the current study, which offers a more natural environment compared to distilled water, adjusting pH levels and natural salt content could more accurately replicate oral cavity conditions, such as the presence of saliva. By optimizing these factors, it would be possible to enhance emulsion stability and fatty acid bioavailability at lower concentrations. This approach provides a potential pathway to better simulate the oral environment, improving the reliability and reproducibility of fat-taste sensitivity measurements, especially at lower concentrations, and ensuring that the measured thresholds are as physiologically relevant as possible.

4. Conclusion

This study examined individual differences in the effects of practice and learning on fat-taste thresholds across repeated measurements and their correlations to other taste sensitivities. Using an SDT-based, descending-block DR A-Not A procedure with a surfactant/additive-free emulsion, classification into hyposensitive versus hypersensitive groups changed when repetition was considered, indicating that task-specific learning can influence threshold-based grouping. In contrast, single-visit grouping showed no association with other tastes, whereas repetition-aware grouping revealed higher PROP bitterness sensitivity in the hypersensitive group, suggesting that learning effects can mask cross-modal relationships if unaccounted for.

Methodologically, simplifying the emulsion matrix and incorporating targeted repetition around the mid-range decision block provides a practical approach to more reliable, learning-aware threshold estimation. This study suggests that focused repetition within a single mid-range decision block (e.g., Steps 3–7) could enhance the stability of fat-taste sensitivity classification. Furthermore, optimizing the pH and salt concentration of the emulsion could improve the stability of fatty acid delivery, creating a more physiologically relevant oral environment for fat-taste testing. These results suggest that the routine use of limited repeats focused on the concentration range that separates hyper- and hyposensitive groups (e.g., repeatedly testing a single mid-range decision block, such as Steps 3–7, rather than running multiple whole descending blocks) or a brief two-session protocol may be sufficient to improve the stability of fat-taste sensitivity classification and facilitate the exploration of its associations with other traits. Interpretation should consider study constraints, including a phenotypically similar cohort of young Korean females and the lack of measures such as fungiform papillae density, dietary fat intake, and genetic variation, which warrant inclusion in future work.

CRediT authorship contribution statement

Ji-Yun Hong: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Seo-Jung Noh:** Writing – review & editing, Investigation. **Ji-Yun Yang:** Writing – review & editing, Methodology, Investigation. **Myoung-Ji Kim:** Writing – review & editing, Investigation. **Jin-Byung Park:** Writing – review & editing. **Hye-Seong Lee:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Acknowledgments

This research was supported by the OTTOGI HAM TAIHO FOUNDATION and was also supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. RS-2023-00218150). The authors would like to specifically thank Ye-Eun Park for supporting data analysis and Dr. Hansol Doh for helping measure the flow behavior of the stimuli used in the oleic acid detection threshold experiment.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2025.118074.

Data availability

Data will be made available on request.

References

Angulo, O., Lee, H. S., & O'Mahony, M. (2007). Sensory difference tests: Overdispersion and warm-up. *Food Quality and Preference, 18*(2), 190–195. https://doi.org/10.1016/j.foodqual.2005.09.015

Asano, M., Hong, G., Matsuyama, Y., Wang, W., Izumi, S., Izumi, M., & Kudo, T. A. (2016). Association of oral fat sensitivity with body mass index, taste preference, and eating habits in healthy Japanese young adults. *The Tohoku Journal of Experimental Medicine, 238*(2), 93–103. https://doi.org/10.1620/tjem.238.93

Bartoshuk, L. M., Duffy, V. B., Green, B. G., Hoffman, H. J., Ko, C. W., Lucchina, L. A., & Weiffenbach, J. M. (2004). Valid across-group comparisons with labeled scales: The gLMS versus magnitude matching. *Physiology & Behavior, 82*(1), 109–114. https://doi.org/10.1016/j.physbeh.2004.02.033

Benjamin, A. S., Tullis, J. G., & Lee, J. H. (2013). Criterion noise in ratings-based recognition: Evidence from the recognition heuristic. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(5), 1601–1611. https://doi.org/10.1037/a0031849

Catherine, J. P., Russell, M. V., & Peter, C. H. (2021). The impact of race and socioeconomic factors on paediatric diabetes. *EClinicalMedicine, 42*. https://doi.org/10.1016/j.eclinm.2021.101186

Choi, J. W., Hong, J. Y., Park, J. B., & Lee, H. S. (2023). Variability of oral/taste sensitivity to fat: An investigation of attribution from two detection threshold methods with repeated measurements. *Food Research International, 165*, Article 112432. https://doi.org/10.1016/j.foodres.2022.112432

Costanzo, A. (2024). Temporal patterns in taste sensitivity. *Nutrition Reviews, 82*(6), 831–847. https://doi.org/10.1093/nutrit/nuad097

Costanzo, A., & Hartley, I. (2025). A simple emulsion for measuring fat taste sensitivity. *Food ResearchInternational, 116515*. https://doi.org/10.1016/j.foodres.2025.116515

Costanzo, A., Russell, C. G., Lewin, S., & Keast, R. (2020). A fatty acid mouth rinse decreases self-reported hunger and increases self-reported fullness in healthy Australian adults: A randomized crossover trial. *Nutrients, 12*(3), 678. https://doi.org/10.3390/nu12030678

Drewnowski, A., Henderson, S. A., & Barratt-Fornell, A. (1998). Genetic sensitivity to 6-n-propylthiouracil and sensory responses to sugar and fat mixtures. *Physiology & Behavior, 63*(5), 771–777. https://doi.org/10.1016/S0031-9384(97)00540-4

Drewnowski, A., Henderson, S. A., & Cockroft, J. E. (2007). Genetic sensitivity to 6-n-propylthiouracil has no influence on dietary patterns, body mass indexes, or plasma lipid profiles of women. *Journal of the American Dietetic Association, 107*(8), 1340–1348. https://doi.org/10.1016/j.jada.2007.05.013

Duffy, V. B., & Bartoshuk, L. M. (2000). Food acceptance and genetic variation in taste. *Journal of the American Dietetic Association, 100*(6), 647–655. https://doi.org/10.1016/S0002-8223(00)00191-7

Ferreira, D. A., Bentley, M. V. L., Karlsson, G., & Edwards, K. (2006). Cryo-TEM investigation of phase behaviour and aggregate structure in dilute dispersions of monoolein and oleic acid. *International Journal of Pharmaceutics, 310*(1–2), 203–212. https://doi.org/10.1016/j.ijpharm.2005.11.028

Flores, F. C., Ribeiro, R. F., Ourique, A. F., Rolim, C. M. B., Silva, C. D. B. D., Pohlmann, A. R., & Guterres, S. S. (2011). Nanostructured systems containing an essential oil: Protection against volatilization. *Química Nova, 34*, 968–972. https://doi.org/10.1590/S0100-40422011000600010

Gaillard, D., & Kinnamon, S. C. (2019). New evidence for fat as a primary taste quality. *Acta Physiologica (Oxford, England), 226*(1), Article e13246. https://doi.org/10.1111/apha.13246

Graham, C. A., Pilic, L., King, A., Nixon, J. E., Pipe, J., Holton, J., & Mavrommatis, Y. (2021). Genetic differences in fat taste sensitivity and dietary intake in a UK female cohort. *Food Quality and Preference, 92*, Article 104202. https://doi.org/10.1016/j.foodqual.2021.104202

Graham, C. A. M., Pilic, L., McGrigor, E., Brown, M., Easton, I. J., Kean, J. N., & Mavrommatis, Y. (2021). The associations between bitter and fat taste sensitivity, and dietary fat intake: Are they impacted by genetic predisposition? *Chemical Senses, 46*, Article bjab029. https://doi.org/10.1093/chemse/bjab029

Guo, S. W., & Reed, D. R. (2001). The genetics of phenylthiocarbamide perception. *Annals of Human Biology, 28*(2), 111–142. https://doi.org/10.1080/03014460151056310

Haryono, R. Y., Sprajcer, M. A., & Keast, R. S. (2014). Measuring oral fatty acid thresholds, fat perception, fatty food liking, and papillae density in humans. *JoVE (Journal of Visualized Experiments), 88*, Article e51236. https://doi.org/10.3791/51236

Hautus, M. J. (2021). SDT assistant (version 2.0) [computer software] Auckland, New Zealand. Available from https://hautus.org/sdt-assistant.php.

Hautus, M. J., Macmillan, N. A., & Creelman, C. D. (2021). Detection theory: A user's guide. Routledge https://doi.org/10.4324/9781003203636.

Hautus, M. J., Shepherd, D., & Peng, M. (2011). Decision strategies for the a not-a, 2AFC, and 2AFC-reminder tasks: Empirical tests. *Food Quality and Preference, 22*(5), 433–442. https://doi.org/10.1016/j.foodqual.2011.02.008

Hautus, M. J., Van Hout, D., & Lee, H. S. (2009). Variants of a not-a and 2AFC tests: Signal detection theory models. *Food Quality and Preference, 20*(3), 222–229. https://doi.org/10.1016/j.foodqual.2008.10.002

Heinze, J. M., Costanzo, A., Baselier, I., Fritsche, A., Lidolt, M., Hinrichs, J., & Keast, R. (2017). Oil perception—Detection thresholds for varying fatty stimuli and inter-individual differences. *ChemicalSenses, 42*(7), 585–592. https://doi.org/10.1093/chemse/bjx039

Heinze, J. M., Preissl, H., Fritsche, A., & Frank, S. (2015). Controversies in fat perception. *Physiology & Behavior, 152*, 479–493. https://doi.org/10.1016/jphysbeh2015.08.033

Keast, R. S., Azzopardi, K. M., Newman, L. P., & Haryono, R. Y. (2014). Impaired oral fatty acid chemoreception is associated with acute excess energy consumption. *Appetite, 80*, 1–6. https://doi.org/10.1016/j.appet.2014.04.022

Kim, M. A., Kim, S. M., & Lee, H. S. (2023). Oral/taste sensitivity to non-esterified long-chain fatty acids with varying degrees of unsaturation. *Food Science and Biotechnology, 33*, 599–606. https://doi.org/10.1007/s10068-023-01502-y

Kim, S. M., Kim, J. E., & Lee, H. S. (2021). Investigation of human flavor perception and discrimination of the fat content in food using DR a-not A and 3-AFC methods. *Food Science and Biotechnology, 30*(6), 815–822. https://doi.org/10.1007/s10068-021-00922-y

Kim, U. K., Jorgenson, E., Coon, H., Leppert, M., Risch, N., & Drayna, D. (2003). Positional cloning of the human quantitative trait locus underlying taste sensitivity to phenylthiocarbamide. *Science, 299*(5610), 1221–1225. https://doi.org/10.1126/science.1080190

Kimura, I., Ichimura, A., Ohue-Kitano, R., & Igarashi, M. (2019). Free fatty acid receptors in health and disease. *Physiological Reviews*. https://doi.org/10.1152/physrev.00041.2018

Lee, H. S., & O'Mahony, M. (2007). Some new approaches to consumer acceptance measurement as a guide to marketing. *Food Science and Biotechnology, 16*(6), 863–867. https://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE01728854.

Lee, H. S., vanHout, D., & Hautus, M. J. (2007). Comparison of performance in the a-not A, 2-AFC, and same–different tests for the flavor discrimination of margarines: The effect of cognitive decision strategies. *Food Quality and Preference, 18*(6), 920–928. https://doi.org/10.1016/j.foodqual.2007.03.008

Lee, S. G., Koh, D. C., Ha, K., Ko, K. S., Lee, Y. S., Jung, Y. Y., … Chen, S. S. (2021). Geochemical implication of chemical composition of mineral. *Water, 13*(16), 2191. https://doi.org/10.3390/w13162191 (Bottled Water) Produced Near Mt. Baekdu (Changbai), Northeast China. Water.

Mattes, R. D. (2005). Fat taste and lipid metabolism in humans. *Physiology & Behavior, 86*(5), 691–697. https://doi.org/10.1016/j.physbeh.2005.08.058

Mun, J. W., Kim, M. A., Sim, H. M., & Lee, H. S. (2019). Investigation of test performance of the dual reminder a-not A (DR a-not A) in comparison to 3-AFC for discriminating samples of drinking water. *Food Quality and Preference, 77*, 43–50. https://doi.org/10.1016/j.foodqual.2019.05.008

Newman, L. P., & Keast, R. S. (2013). The test–retest reliability of fatty acid taste thresholds. *Chemosensory Perception, 6*(2), 70–77. https://doi.org/10.1007/s12078-013-9143-2

Nolden, A. A., McGeary, J. E., & Hayes, J. E. (2020). Predominant qualities evoked by quinine, sucrose, and capsaicin associate with PROP bitterness, but not TAS2R38

genotype. *Chemical Senses, 45*(5), 383–390. https://doi.org/10.1093/chemse/bjaa028

O'Mahony, M., & Hautus, M. J. (2008). The signal detection theory ROC curve: Some applications in food sensory science. *Journal of Sensory Studies, 23*(2), 186–204. https://doi.org/10.1111/j.1745-459X.2007.00149.x

Pinto, M. F., Moura, C. C., Nunes, C., Segundo, M. A., Lima, S. A. C., & Reis, S. (2014). A new topical formulation for psoriasis: Development of methotrexate-loaded nanostructured lipid carriers. *International Journal of Pharmaceutics, 477*(1–2), 519–526. https://doi.org/10.1016/j.ijpharm.2014.10.067

Rai, V. (2024). High-fat diet, epigenetics, and atherosclerosis: A narrative review. *Nutrients, 17*(1), 127. https://doi.org/10.3390/nu17010127

Robino, A., Concas, M. P., Spinelli, S., Pierguidi, L., Tepper, B. J., Gasparini, P., & Dinnella, C. (2022). Combined influence of TAS2R38 genotype and PROP phenotype on the intensity of basic tastes, astringency, and pungency in the Italian taste project. *Food Quality and Preference, 95*, Article 104361. https://doi.org/10.1016/j.foodqual.2021.104361

Running, C. A., Craig, B. A., & Mattes, R. D. (2015). Oleogustus: The unique taste of fat. *Chemical Senses, 40*(7), 507–516. https://doi.org/10.1093/chemse/bjv036

Running, C. A., & Mattes, R. D. (2014). Different oral sensitivities to and sensations of short-, medium-, and long-chain fatty acids in humans. *American Journal of Physiology-Gastrointestinal and Liver Physiology, 307*(3), G381–G389. https://doi.org/10.1152/ajpgi.00181.2014

Running, C. A., Mattes, R. D., & Tucker, R. M. (2013). Fat taste in humans: Sources of within-and between-subject variability. *Progress in Lipid Research, 52*(4), 438–445. https://doi.org/10.1016/j.plipres.2013.04.007

Skoczek-Rubińska, A., Chmurzynska, A., Muzsik-Kazimierska, A., & Bajerska, J. (2021). The association between fat taste sensitivity, eating habits, and metabolic health in menopausal women. *Nutrients, 13*(12), 4506. https://doi.org/10.3390/nu13124506

Sollai, G., Melis, M., Mastinu, M., Pani, D., Cosseddu, P., Bonfiglio, A., & Tomassini Barbarossa, I. (2019). Human tongue electrophysiological response to oleic acid and its associations with PROP taster status and the CD36 polymorphism (rs1761667). *Nutrients, 11*(2), 315. https://doi.org/10.3390/nu11020315

Stewart, J. E., Feinle-Bisset, C., Golding, M., Delahunty, C., Clifton, P. M., & Keast, R. S. (2010). Oralsensitivity to fatty acids, food consumption and BMI in human subjects. *British Journal of Nutrition, 104*(1), 145–152. https://doi.org/10.1017/S0007114510000267

Stewart, J. E., Newman, L. P., & Keast, R. S. (2011). Oral sensitivity to oleic acid is associated with fat intake and body mass index. *Clinical Nutrition, 30*(6), 838–844. https://doi.org/10.1016/j.clnu.2011.06.007

Suga, K., Kondo, D., Otsuka, Y., Okamoto, Y., & Umakoshi, H. (2016). Characterization of aqueous oleic acid/oleate dispersions by fluorescent probes and Raman spectroscopy. *Langmuir, 32*(30), 7606–7612. https://doi.org/10.1021/acs.langmuir.6b02257

Sugiyama, S., Matsuoka, D., Hara, T., Sonoyama, M., Matsuoka, S., & Murata, M. (2022). Experimental and theoretical investigations into the mechanism of interactions between membrane-bound fatty acids and their binding protein: A model system to investigate the behavior of lipid acyl chains in contact with proteins. *Chemistry and Physics of Lipids, 247*, Article 105227. https://doi.org/10.1016/j.chemphyslip.2022.105227

Tepper, B. J., & Nurse, R. J. (1997). Fat perception is related to PROP taster status. *Physiology & Behavior, 61*(6), 949–954. https://doi.org/10.1016/S0031-9384(96)00608-7

Tepper, B. J., & Nurse, R. J. (1998). PROP taster status is related to fat perception and preference a. *Annals of the New York Academy of Sciences, 855*(1), 802–804. https://doi.org/10.1111/j.1749-6632.1998.tb10662.x

Tucker, R. M., & Mattes, R. D. (2013). Influences of repeated testing on nonesterified fatty acid taste. *Chemical Senses, 38*(4), 325–332. https://doi.org/10.1093/chemse/bjt002

Turner, B. M., Van Zandt, T., & Brown, S. (2011). A dynamic stimulus-driven model of signal detection. *Psychological Review, 118*(4), 583. https://doi.org/10.1037/a0025191

Wali, J. A., Jarzebska, N., Raubenheimer, D., Simpson, S. J., Rodionov, R. N., & O'Sullivan, J. F. (2020). Cardio-metabolic effects of high-fat diets and their underlying mechanisms—A narrative review. *Nutrients, 12*(5), 1505. https://doi.org/10.3390/nu12051505

World Health Organization, Regional Office for the Western Pacific. (2000). *The Asia-Pacific perspective: Redefining obesity and its treatment*. Sydney: Health Communications Australia. http://iris.wpro.who.int/handle/10665.1/5379.

Yang, J. Y., Park, J. B., & Lee, H. S. (2025). Improving oral fat sensitivity measurement and evaluating key fat types using a modified signal detection approach and additive-free milk-based emulsions. *Food Science and Biotechnology, 34*, 3607–3616. https://doi.org/10.1007/s10068-025-01985-x

Zhou, X., Shen, Y., Parker, J. K., Kennedy, O. B., & Methven, L. (2016). Relative effects of sensory modalities and importance of fatty acid sensitivity on fat perception in a real food model. *Chemosensory Perception, 9*(3), 105–119. https://doi.org/10.1007/s12078-016-9211-5