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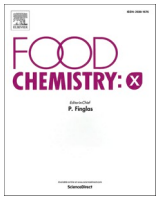

Evaluation of perceptual interactions between key aldehydes in Kung Pao Chicken

Shengchao Lin, Na Li, Xingtao Zhou, Songling Li, Aiping Yang, Jiao Zhou, Ping Liu *

School of Food and Bioengineering, Xihua University, Chengdu 610039, Sichuan, People's Republic of China

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ABSTRACT

Aldehydes are the strongest and most abundant aromatic compounds in Kung Pao Chicken. However, the perceptual interactions between these aldehydes are not fully understood. Therefore, the flavor contribution of nine key aldehydes was estimated by determining thresholds. Except for benzaldehyde, the thresholds of all aldehydes measured in tasteless chicken matrices (TM) were significantly larger than their comparable values in water. Based on these results, the perceptual interactions of nine aldehydes were evaluated using S-curves and σ-τ plots. The interactions indicated that 31 of their 36 binary mixtures exhibited additive effects, three had masking effects, while two had synergistic effects. Recombination experiments showed that the addition of aldehydes lowered the odor threshold of aldehyde reconstitution (AR), thereby enhancing the aroma intensity of AR. These findings contribute to a better understanding of Kung Pao Chicken's aroma and can be used to improve its aroma quality.

1. Introduction

Kung Pao Chicken is a traditional Chinese chicken cuisine, treasured throughout the ages for its distinctive color, aroma and taste (Ma, Zhang, Xu, & Bai, 2020). Aroma, one of the first stimuli experienced before food consumption, is an important sensory characteristic and among those used to assess food quality (Calin-Sanchez & Carbonell-Barrachina, 2021). Thus, aroma perception plays a pivotal role in consumers' overall sensory experience and acceptance or rejection of food (Lezaeta, Bordeu, Agosin, Perez-Correa, & Varela, 2018).

Currently, the ingredients for Kung Pao Chicken are readily available from a variety of suppliers but with unclear constituent ratios, resulting in varied finished-product quality. Key aroma molecules in food can induce aroma perception in the human brain via interactions with olfactory organs (Dunkel et al., 2014), and exploring these sensory interactions and perception mechanisms can reveal important information about food quality. Aldehydes, for example, which have a low odor threshold, are associated with the formation of fatty and meaty flavors, as well as those of orange peel and lemon, which contribute considerably to the overall aroma of Kung Pao Chicken (Cui et al., 2021; Zeng, Liu, Dong, Bai, Yu, & Li, 2019). In our previous study (The results of this study are being submitted for publication), the 22 key aroma compounds and flavor components in Kung Pao Chicken were identified, of which aldehydes constituted 40.91 %, however, their interactions had yet to be thoroughly explained.

The threshold method, the S-curve method, the odor activity value (OAV) method, and the σ-τ plot are effectively used to understand perceptual interactions (Berglund, Berglund, & Lindvall, 1976). Through these approaches, the interactions between components can be determined by comparing the changes that occur in thresholds, OAVs and odor intensities following the combination of aroma components. The S-curve and σ-τ plot approaches, in particular, are reportedly highly accurate and practical in the investigation of interactions between aroma components in fragrances (Chen, Zhou, Yu, Yuan, & Tian, 2020). According to Lytra, Tempere, Le Floch, de Revel and Barbe (2013), the use of the S-curve method revealed that ethyl-3-hydroxybutanoate and 2-methylpropyl acetate have a synergistic effect that decreases the odor threshold of fruit flavors while increasing overall aroma intensity. Niu, Zhang, Xiao and Zhu (2020) used the σ-τ plot technique to assess the perceptual interactions of six higher alcohols and three off-odor acids, and found that the addition of high concentrations of 1-propanol or 2-phenylethanol to a white wine matrix could mask the sweaty odor of 3-methylbutyric acid. Xiao, Xiang, Zhu, Zhu, Liu and Niu (2019) investigated the interactions between sulfur-containing compounds in mangoes, they reported that six mixtures had masking effects, while three mixtures had additive effects, and one mixture had synergistic

* Corresponding author.
E-mail address: dewflowerlp@163.com (P. Liu).

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effects. The perceptual interactions of the food aromas found in other fruits, wines and dairy products have also been the subjects of numerous similar investigations, however, data regarding the perceptual interactions of meat products' aromas are still limited.

This study aims to elucidate the perceptual interactions between the aldehydes in Kung Pao Chicken and their contributions to the overall aroma of this popular dish. Firstly, the odor thresholds of hexanal, heptanal, octanal, 1-nonanal, 3-(methylthio) propionaldehyde, citronellal, decyl aldehyde, benzaldehyde and phenylacetaldehyde in the matrix of Kung Pao Chicken were determined. Subsequently, the perceived interactions between these nine compounds were evaluated using the S-curve and σ-τ plot methods. Additionally, the effects of individual aldehydes on aldehyde reconstitution (AR) were investigated to understand the interaction patterns among aroma molecules in Kung Pao Chicken. The results herein may contribute to an in-depth understanding of the aldehydes responsible for the fatty and meaty odors of Kung Pao Chicken. The provision of such information can be used to improve cooking techniques, ingredient formulations and sensory experiences, thereby helping to achieve desirable organoleptic properties in final products.

2. Materials and methods

2.1. Chemicals and samples

Hexanal (99.0 %), heptaldehyde (98.0 %), citronellal (98.0 %) and benzaldehyde (99.5 %) were purchased from Macklin Biochemical Co., Ltd. (Shanghai, China); 1-nonanal (98.0 %), decyl aldehyde (98.0 %), and phenylacetaldehyde (98.0 %) were purchased from yuanye Bio-Technology Co., Ltd. (Shanghai, China); octanal (98.0 %) was purchased from Sigma-Aldrich (Shanghai, China); and 3-(methylthio) propionaldehyde (97.0 %) was purchased from TCL Technology (Shanghai, China). All of these chemical standards were of GC quality. The Kung Pao Chicken sample was obtained from the St. Regis Hotel (Chengdu, China), code B1.

A tasteless chicken matrix (TM) was prepared as follows: dichloromethane, methanol and *n*-pentane were added into the B1 sample (the ratio of dichloromethane, methanol, *n*-pentane and chicken was 1:1:1:1, m/m/m/m). The mixture was agitated on a HNY-2102C shaker (Tianjin Honour Instrument Co., Ltd, Tianjin, China) at 25 °C for 8 h, and then filtered to remove the organic solvents. This procedure was repeated until the sample had lost its odor. The odorless residue was then freeze-dried for 12 h and, subsequently, was combined and mixed with the same water content as that in the B1 to create the TM.

For AR, various aldehydes were selectively added to the TM at the same concentrations as those in the B1 (Table 1a). The total aldehyde reconstitution (TAR) was the combination of all nine aldehydes.

2.2. Gas chromatography–olfactometry/mass spectrometry (GC-O/MS) analysis of reference compounds

GC-O/MS analysis was conducted to ensure the absence of any odorous impurities in the flavor standards. The olfactory analysis was performed using an olfactometer (ODP-3, Gerstal, Mulheim an der Ruhr, Germany), with a DB-Wax column (30 m × 320 μm × 0.25 μm, Agilent Technologies, Santa Clara, CA, USA). The pure flavor standard (1 μL) was injected directly via liquid injection (injector temperature, 250 ℃; carrier gas, helium; flow rate, 1.0 mL/min; no diversion). The separation via the DB-Wax column enabled the sample to flow into the MS detector and sniff port at a 1:1 (v/v) ratio. The heating procedure was established as follows: initial temperature 40 ℃, held for 2 min, then increased to 240 °C at a rate of 6 °C/min. The MS conditions were set as follows: electron ionization source (EI), electron energy of 70 eV, and a mass scan range of 41 *m/z* ~ 330 *m/z*. The transmission line temperature was maintained at 250 °C, while the ion source and sniffing port temperatures were 230 °C and 80 °C, respectively.

Table 1a
Concentrations of key aldehydes in Kung Pao Chicken B1, accompanied by their flavour description and threshold values found in literature.

No	Aldehydes [a]	Concentration [b] (μg/kg)	Threshold [c] (μg/kg)	Flavour description
1	hexanal	731.29 ± 80.33c [d]	5.00	Oil, grass, apple
2	heptaldehyde	100.09 ± 10.67f	2.80	Apricot, nut, grass, oil
3	octanal	22.97 ± 6.78i	0.59	Oil, orange
4	1-nonanal	77.47 ± 5.30 g	1.10	Oil, orange
5	3-(methylthio) propionaldehyde	206.58 ± 29.99e	0.45	Onion, meat
6	citronellal	41.08 ± 8.80 h	6.00	Orange, lemon, rose
7	decyl aldehyde	585.16 ± 18.86d	3.00	Oil, orange
8	benzaldehyde	791.40 ± 37.55b	750.89	Almond, sweet
9	phenylacetaldehyde	1999.28 ± 109.77a	6.30	Almond, sweet

[a] Key aldehydes for sample B1.
[b] Standard deviation over average concentration.
[c] The detection threshold in water taken from the literature.
[d] Values with different letters (a-i) in the same row are significantly different according to Duncan's test ($p < 0.05$).

Each sample was analyzed in triplicate, and the results revealed no irritating odors in the purchased flavor standards. Moreover, the hydrogen flame ionization detector (FID) demonstrated the purity of the employed substances, further ensuring zero interference with the subsequent series of experiments.

2.3. Sensory analysis

2.3.1. General conditions and sensory panel

Sensory analysis was performed as described by Martin and de Revel (1999). All sensory experiments were conducted in a professional sensory analysis laboratory with a room temperature of 25 ± 2 °C, adequate ventilation and normal lighting. Samples were placed in capped, odorless brown vials and were left to equilibrate for 10 min before being subjected to the sensory evaluations. Each sample was coded with a random three-digit number. The test was repeated three times.

The sensory panel consisted of 10 evaluators (five males and five females, aged 22–25 years, with no olfactory impairments), who were seated in individual compartments. All panel members had extensive sensory experience and were from the School of Food and Bioengineering, Xihua University (Chengdu, China). Prior to the formal experiment, all evaluators participated in a training course involving three 1-hour sessions per week for four weeks, to ensure that they would be able to accurately distinguish aroma characteristics according to odor types.

2.3.2. Determination of odor threshold

The three alternative forced-choice (3-AFC) method was used by the sensory evaluators to determine the thresholds of the aroma substances in the samples. The detection probabilities and logarithmic concentrations of compounds conformed to an S-shaped curve, enabling the determination of each compound's threshold based on the probability of detection (Cometto-Muniz & Abraham, 2015). Based on the quantitative results established for the aroma compounds, 10 concentration points were prepared by dilution in two-fold stages. Solutions with different gradients were added to the TM to form 10 test groups, each comprised of one sample to be tested and two reference samples. The sensory evaluators performed their sniffing in the order of high to low concentrations. If the panelists were able to correctly identify the aroma of the same sample in both trials, the test continued with the sample at the next lower concentration. The process continued until the evaluators were unable to identify an aroma. Their evaluations were recorded and the results of all tests were subsequently statistically analyzed. The odor

threshold was defined as the concentration at which the probability of detection was 50 %.

Odor thresholds of the binary mixtures and AR were also measured, with those of the AR determined in two different matrices: TM, and the TM containing the target compounds (Table 1b).

2.4. Perceptional interaction analysis

2.4.1. S-curve method using Feller's additive model

The S-curve approach uses the 3-AFC method to generate a series of concentrations-probability (C—P) curves for different aroma compounds. In this study, a total of 10 concentration gradients were set up, with each group containing one positive sample and two blanks. The sensory panel then assessed the detection probability of the compounds, which was calculated as the ratio of the number of correct responses to the total number of panel members. Detection probability was corrected using the chance factor formula $P = (3*p - 1)/2$, where p is the proportion of correct responses for each concentration, and P is the proportion corrected for chance.

The psychometric concentration-probability function was found to conform to the S-curve equation, $P = \frac{1}{1+\exp[-(x-c)/D]}$, where P is the detection probability, x is the logarithmic concentration of aroma compounds, e is Napier's constant, c is the logarithmic threshold, and D is the function steepness. Here, when the ordinate P is 0.5, the corresponding abscissa represents the actual detection threshold of the compound. Origin 2018 software was used for graphic analysis.

In addition, interaction effects in the mixtures were evaluated using Feller's (1968) additive model, as developed by Miyazawa, Gallagher, Preti and Wise (2008). The theoretical detection probability P(AB) of each mixture was defined as P(AB) = P(A) + P(B) - P(A)P(B), where P(A) is the actual detection probability of compound A, and P(B) is the actual detection probability of compound B. The type of interaction between substances was determined based on the ratio (R) of the actual detection threshold to the theoretical threshold as follows: if $R > 1$, a masking effect; if $R = 1$, no effect; if $0.5 \leq R < 1$, an additive effect; if $R < 0.5$, a synergistic effect will take place.

2.4.2. σ-τ plot method

Types of interactions can also be determined using the σ-τ plot method. Herein, 53 % ethanol aqueous solution (level 0) and 53 % ethanol aqueous solutions of 1-butanol [levels 1 (10 ppm) to level 12 (20480 ppm)] were used to make a 0–12 point odor intensity referencing scale (OIRS) (0 = no odor, 12 = very strong) (Atanasova, Langlois, Nicklaus, Chabanet, & Etiévant, 2004). The panelists employed the OIRS to evaluate the odor intensity of a single compound or mixtures under static conditions after aroma intensity training. The odor intensity determined for each sample was represented by the triplicate means value.

In the [σ = f(τ)] model of the binary mixture intensity proposed by Patte and Laffort (1979), σ represents the ratio of the odor intensity value after A and B are mixed to the sum of individual intensities ($\sigma = I_{AB}/(I_A + I_B)$); τ represents the ratio of the odor intensity of compound A (or B) to the sum of the odor intensities of A and B alone, that is, $\tau_A = I_A/(I_A + I_B)$ and $\tau_B = I_B/(I_A + I_B)$, where I_A and I_B indicate the odor intensity of the component, and I_{AB} indicates the odor intensity of the mixture. If $\sigma > 1$ for hyper-addition, if $\sigma = 1$ for complete addition, but if $\sigma < 1$ for hypo-addition. Frijters (1987) further divided hypo-addition into three stages, namely partial addition, compromise, and subtraction: (1) If max $(I_A, I_B) < I_{AB} \leq I_A + I_B$, it is shown as partial addition; (2) if min $(I_A, I_B) < I_{AB} \leq$ max (I_A, I_B), it is shown as a compromise; and (3) if $I_{AB} \leq$ min (I_A, I_B), it appears as subtraction. In this study, for the statistical test of σ and τ, the mean intensities of the 10 professional evaluators were all within the 95 % confidence interval.

2.5. Statistical analysis

Descriptive data and the differences between samples were analyzed using analysis of variance (ANOVA) and Duncan's test with SPSS (Version 22.0, Chicago, IL, USA). The statistically significant level was 5 % ($P < 0.05$). Origin 2018 (Origin Lab Corporation, Northampton, MA) was used to draw the S-curves (Feller's additive model) and σ-τ plots.

3. Results and discussion

3.1. Flavor compounds' threshold determination

The threshold is defined as the lowest concentration of aroma compound that is naturally sensed by people. Its magnitude depends on factors such as the system in which it is present, evaluation calculations, and the sensory personnel (Yang et al., 2023). Here, the odor thresholds of the nine aldehydes (hexanal, heptanal, octanal, 1-nonanal, 3-(methylthio) propionaldehyde, citronellal, decyl aldehyde, benzaldehyde and phenylacetaldehyde) in the TM were determined via the 3-AFC method to accurately assess the interactions between compounds.

Fig. 1 shows the odor threshold of the nine aldehydes in the TM, in which $R^2 > 0.95$ indicates that the fitting line accurately represented the data. The odor thresholds for hexanal, heptanal, octanal, 1-nonanal, 3-(methylthio)propanal, citronellal, decyl aldehyde and phenylacetaldehyde in the TM were 24.05 μg/kg, 13.06 μg/kg, 3.46 μg/kg, 9.42 μg/kg, 10.30 μg/kg, 10.12 μg/kg, 120.86 μg/kg and 131.14 μg/kg, respectively, all of which are higher values than the odor thresholds reported in the literature (Table 1a) (Van Gemert, 2011), with ratios fluctuating in the range of 2–40. This difference may be due to variations in the measuring matrix used in this experiment compared to the water used in previous studies. Non-volatile matrix components, such as sugars, polyphenols and organic acids affect aroma release (Wang et al., 2022). From this, it was inferred that specific intermolecular forces in the non-volatile compound-aldehyde system induced various aldehyde release behaviors in the TM, thereby affecting human olfactory perception, leading to a higher threshold. This phenomenon is consistent with previous research in which it was shown that low concentrations of organic acids can cause higher detection thresholds for many odorants (Liu, Xi, Fu, Li, Sun, & Zong, 2022).

The measured odor threshold for benzaldehyde, 51.88 μg/kg, was significantly lower than has been previously reported (750.89 μg/kg), representing a deviation of approximately 15-fold. A possible reason for this phenomenon may have been confusion between detection and

Table 1b
Composition of samples subjected to odor threshold determination in various matrices.

No	Sample	AR [a]	Matrix	Reference sample
1	AR1	TAR excluding hexanal	TM [b]; TM + hexanal	TAR [c]
2	AR2	TAR excluding heptaldehyde	TM; TM + heptaldehyde	TAR
3	AR3	TAR excluding octanal	TM; TM + octanal	TAR
4	AR4	TAR excluding 1-nonanal	TM; TM + 1-nonanal	TAR
5	AR5	TAR excluding 3-(methylthio) propionaldehyde	TM; TM + 3-(methylthio) propionaldehyde	TAR
6	AR6	TAR excluding citronellal	TM; TM + citronellal	TAR
7	AR7	TAR excluding decyl aldehyde	TM; TM + decyl aldehyde	TAR
8	AR8	TAR excluding benzaldehyde	TM; TM + benzaldehyde	TAR
9	AR9	TAR excluding phenylacetaldehyde	TM; TM + phenylacetaldehyde	TAR

[a] AR, aldehyde reconstitution.
[b] TM, tasteless chicken matrix.
[c] TAR, total aldehyde reconstitution (including all reference aldehyde compounds).

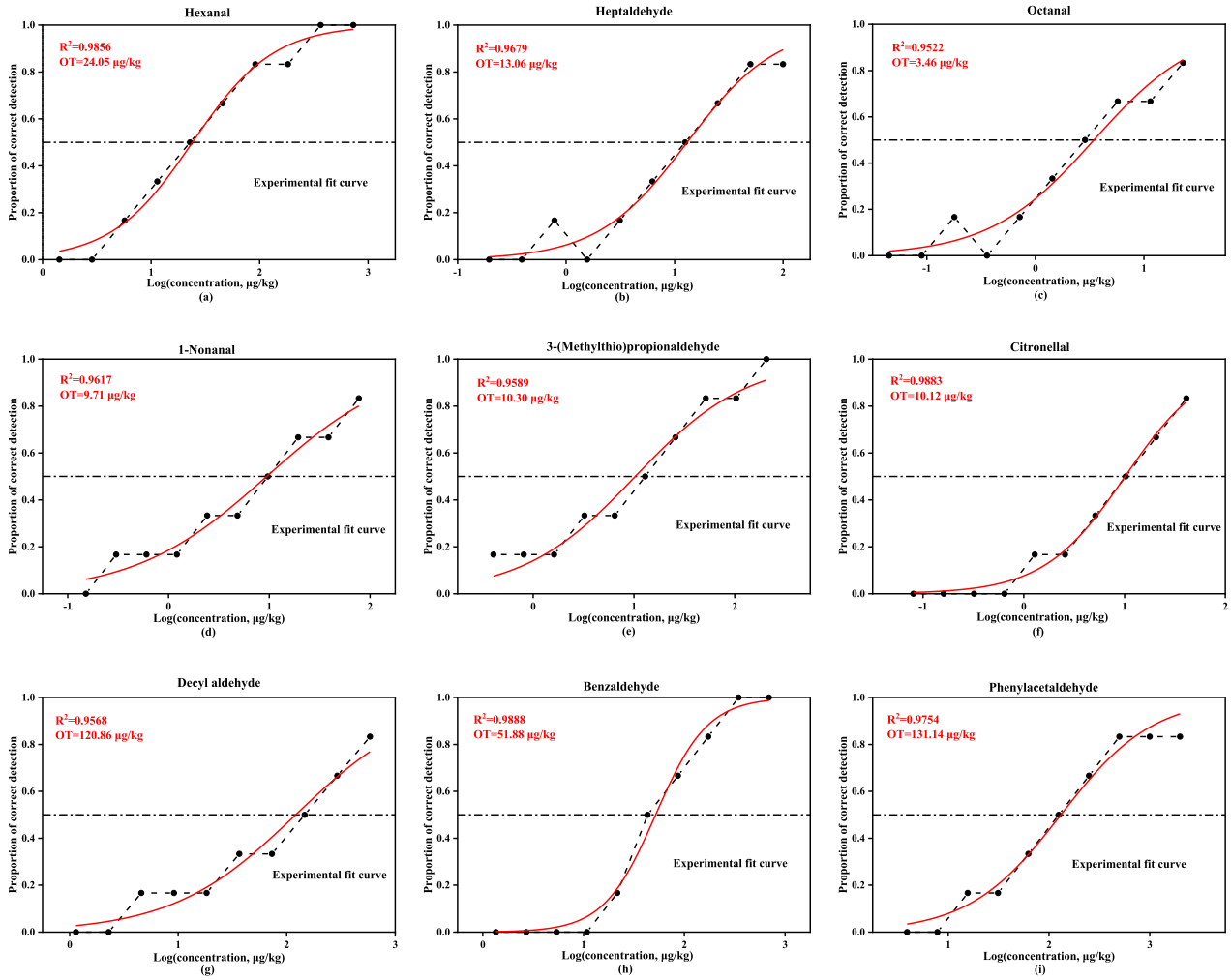


Fig. 1. Odor threshold determination results for 9 key aldehydes: (a) Hexanal, (b) Heptaldehyde, (c) Octanal, (d) 1-Nonanal, (e) 3-(Methylthio)propionaldehyde, (f) Citronellal, (g) Decyl aldehyde (h) Benzaldehyde, and (i) Phenylacetaldehyde. OT, odor threshold. R^2, goodness of fit. The curves are drawn according to S-curves.

recognition thresholds in the experiment, with the latter frequently higher than the former. Additionally, olfactory variations between the *ortho*-nasal (the aroma via the nose) and *retro*-nasal (aroma entering from the mouth) sensory experience can impact judgments (Han et al., 2019). The reference literature has no standardized threshold types, however, *ortho*-nasal thresholds were chosen in this experiment because they relate directly to olfaction and were, thus, considered more appropriate for this study. Finally, variations in thresholds may also be related to the matrix, experimental conditions and sensory personnel (Wang et al., 2021).

The results of the threshold determination experiment highlight the significant impact of matrix composition on odor thresholds. To the best of our knowledge, thresholds are measured mostly in air, aqueous solutions and aqueous ethanol solutions, less frequently, in actual systems. The determination of compound thresholds under the TM in this study can, thus, provide valuable insights and references for other researchers.

3.2. Perceptual interactions between nine key aldehydes

3.2.1. S-curve method using Feller's additive model

To better understand the interactions between the key aldehydes in Kung Pao Chicken, nine aldehydes were added to the TM in 36 binary mixtures according to their actual concentrations, whereafter their aroma interactions were examined using the S-curve approach.

The perceptual interactions in the binary mixtures were evaluated using Feller's additive model, as shown in Fig. 2. In the combinations of heptaldehyde and 1-nonanal, and 1-nonanal and decyl aldehyde, it was found that R values of 0.48 and 0.42, respectively, indicated the presence of aromatic synergy between the pairs (Fig. 2a). In three additional binary combinations, namely hexanal and 1-nonanal, hexanal and phenylacetaldehyde, and decyl aldehyde and benzaldehyde, the experimental thresholds were found to be higher than the theoretical thresholds when the detection probability was 50 %, and their R values of 6.98, 2.37 and 6.12, respectively, indicated the masking effect of these three combined pairs (Fig. 2b). Moreover, the R values of the remaining 31 pairs of binary mixtures were all greater than 0.5 but less than 1, indicating the existence of additive effects between them (Fig. 2c). Among them, the additive effect in the interaction between 3-(methylthio)propanal and phenylacetaldehyde has been consistently reported by Saison, De Schutter, Uyttenhove, Delvaux and Delvaux (2009).

Interactions between eight of the binary mixtures with similar structures exhibited additive effects, namely hexanal and heptanal, hexanal and octanal, hexanal and decyl aldehyde, heptanal and octanal, heptanal and decyl aldehyde, octanal and 1-nonanal, octanal and decyl aldehyde, and benzaldehyde and phenylacetaldehyde. Moreover, heptanal and 1-nonanal, and 1-nonanal and decyl aldehyde had synergistic effects. These findings are consistent with previous studies showing that compounds with similar structures and aromas tend to exhibit additive or synergistic effects (Lytra, Tempere, de Revel, & Barbe, 2014; Yu, Xie,

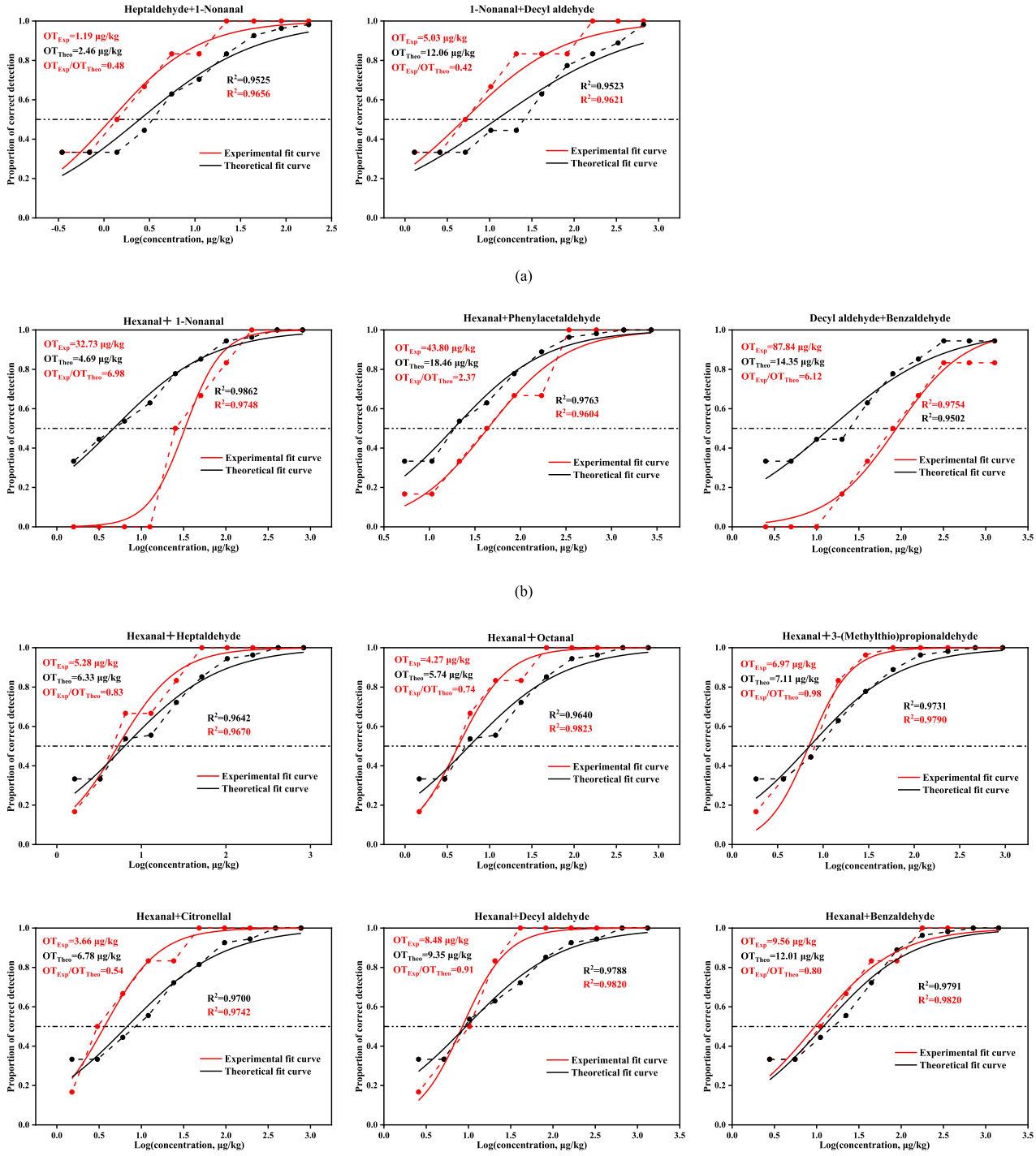


Fig. 2. Perceptual interactions among 36 pairs of binary mixtures: (a) combinations of synergistic effects, (b) combinations of masking effects, (c) combinations of additive effects. OT, odor threshold. R^2, goodness of fit. The curves are drawn according to S-curves.

Xie, Chen, Ai, & Tian, 2020).

Notably, some structurally dissimilar compounds, such as hexanal and benzaldehyde, heptanal and benzaldehyde, and heptanal and phenylacetaldehyde, also exhibited additive effects, a finding similar to that reported by Zhu, Chen, Wang, Niu and Xiao (2017). Other compounds with different structures, namely (E,E)-2,4-hexadienal and phenyl acetaldehyde, and (E)-2-hexenal and phenyl acetaldehyde, showed marginal additive effects. Furthermore, while the structures and aromas of acetaldehyde and nonanal are similar, their interactions showed a masking effect, which contradicts the previous proposition that compounds with similar structures and flavors often exhibit positive interactions. Comparable observations were reported by Sterckx, Missiaen, Saison and Delvaux (2011), who found despite their comparable structures and flavors, vanillin and acetovanillone behaved antagonistically in their interaction This phenomenon may be attributed to factors such as the influence of the sensory panelists' different backgrounds and sensitivities on their evaluations. Moreover, deviations between actual detection threshold and true threshold affected the

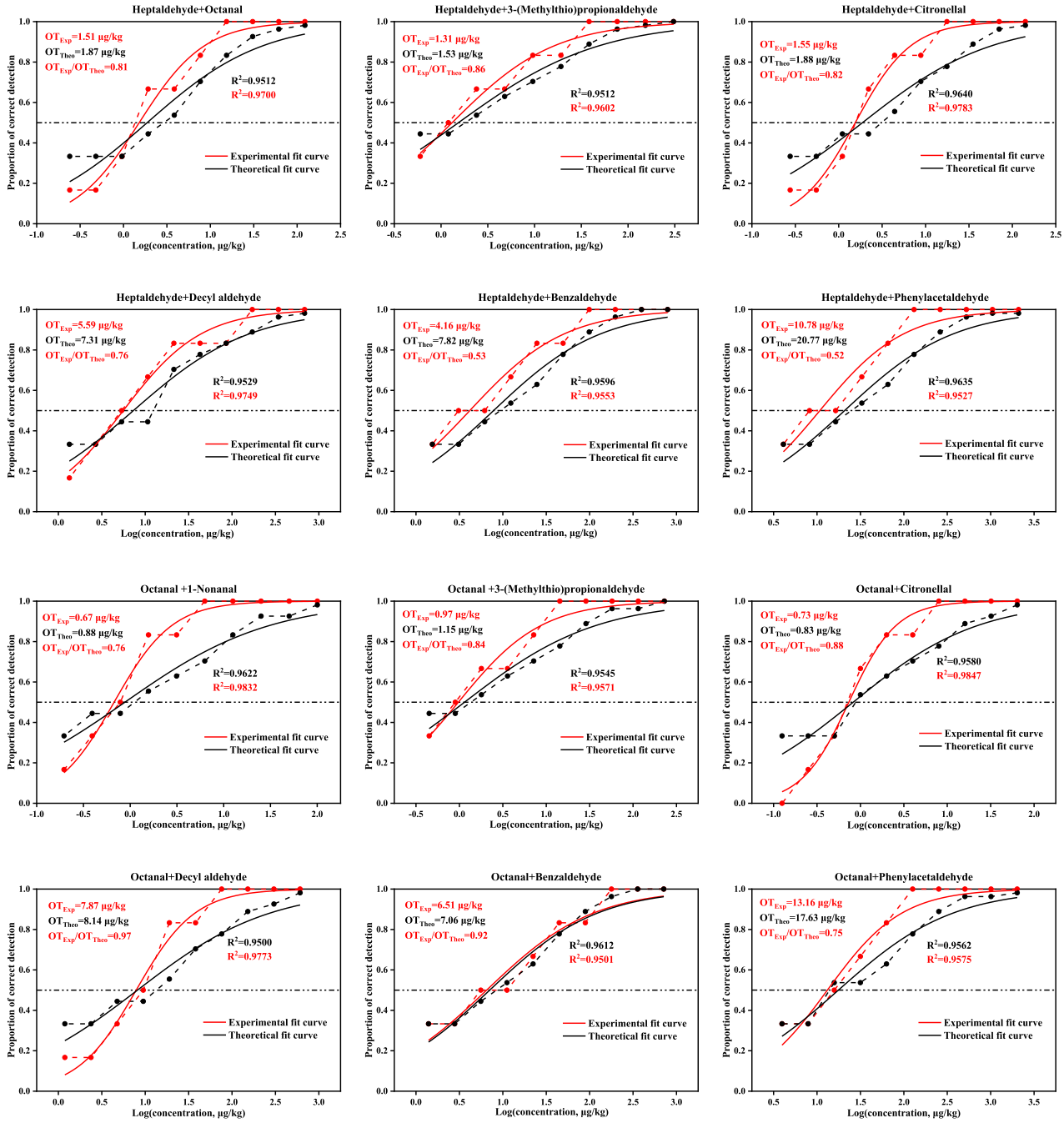


Fig. 2. (*continued*).

interaction relationship between mixtures (Guth, 1997).

3.2.2. σ-τ plot method

The σ-τ plot method was employed to confirm the interactions in binary mixtures, since the intensities of the aroma components varied. This method focuses on aroma intensity rather than concentration, providing clarity to the mixtures' aroma characteristics, and graphically visualizing the data, thereby enabling a comprehensive investigation of aroma component interactions (Berglund, Berglund, Lindvall, & Svensson, 1973; Jones & Woskow, 1964).

In Fig. 3 it can be seen that the σ values of the combined aroma components ranged from 0.39 to 1.04. Masking effects ($\sigma < 1$ and $I_{AB} \leq \min(I_A, I_B)$) were observed in three pairs of aldehydes: hexanal and 1-nonanal, hexanal and phenylacetaldehyde, and decyl aldehyde and benzaldehyde. Additionally, an aromatic synergy was apparent between two groups of mixtures: heptanal and 1-nonanal, and 1-nonanal and decyl aldehyde, with point coordinates (τ, σ) of (0.51, 1.03) and (0.46, 1.04), respectively. A significant synergistic relationship was observed between 1-nonanal and decyl aldehyde ($\sigma = 1.04$). In 31 pairs of binary mixtures, σ fell between 0.5 and 1, with $I_{AB} \leq I_A + I_B$, indicating an additive effect. This result is in line with the earlier study, which showed that the aroma intensity of binary mixtures is often lower than the sum of component intensities (Niu, Yao, Xiao, Zhu, Zhu, & Chen, 2018).

No complete additive effects or compromise effects were observed in the experiment, possibly due to the concentrations of the mixtures. In a study by Cameleyre, Lytra, Tempere and Barbe (2015), the perceived

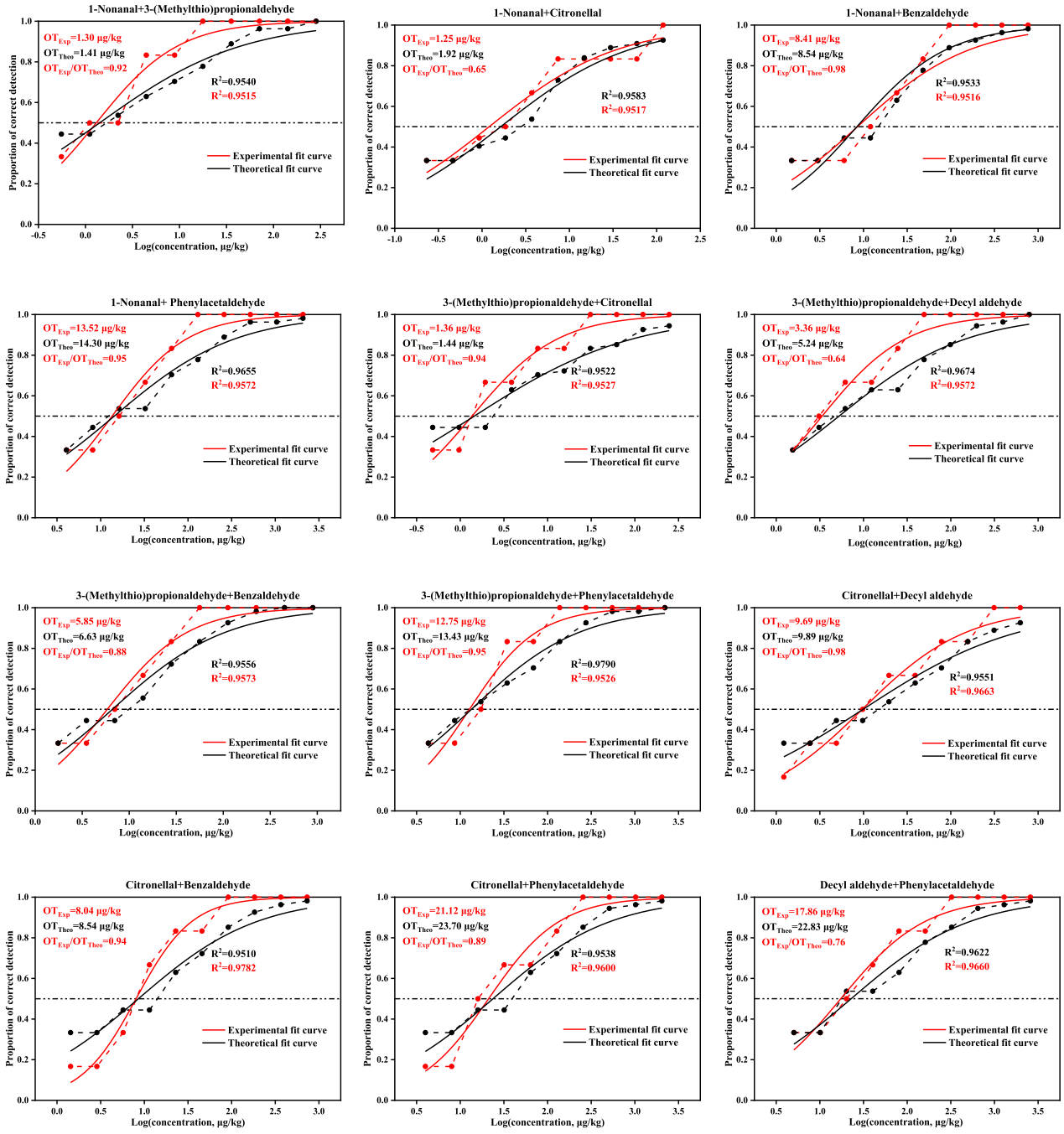


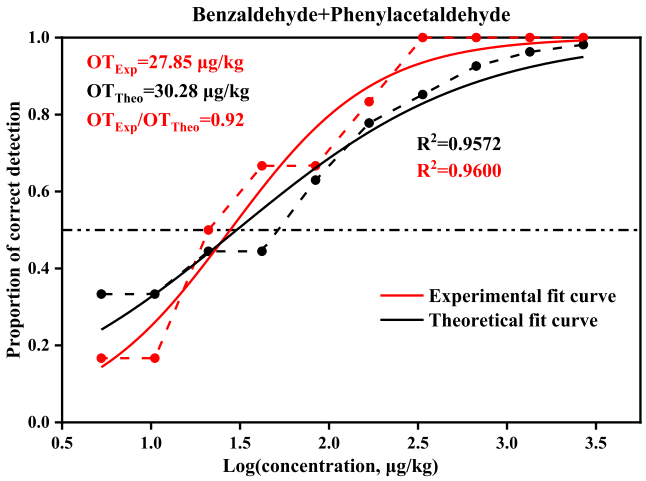
Fig. 2. (*continued*).

interactions between alcohol compounds and wine reconstitution liquid varied according to the variations in alcohol concentration, exhibiting a masking effect at high concentrations, but a synergistic effect at moderate concentrations. These findings suggest that concentration affects the perceived interaction of aroma molecules. Additionally, Mao et al. (2019) discovered that subthreshold concentrations of aroma components added to the initial solution led to synergistic effects with its aroma molecules, further highlighting the importance of aroma concentration in the interaction.

In this study, perceptual interactions via the σ-τ plot method were consistent with the S-curve results. Of the 36 pairs of compounds, 31 binary mixtures were found to have additive effects, while three exhibited masking effects and two had synergistic effects.

3.3. *Comparative analysis of the test discrimination method*

The S-curve approach was used to integrate the threshold and the concentration of aroma components in the analysis of phase interactions. The threshold was calculated using mathematical fitting to enhance its accuracy, while the intensity of aroma components was used as the index of investigation and was graphically presented by the σ-τ plot method. The results were essentially consistent and could be cross-checked when using the two methods to investigate how compounds interact with one another. Therefore, we investigated the effects of aldehydes on AR thresholds in subsequent experiments using both the S-curve approach and the σ-τ plot method.



(c)

Fig. 2. (*continued*).

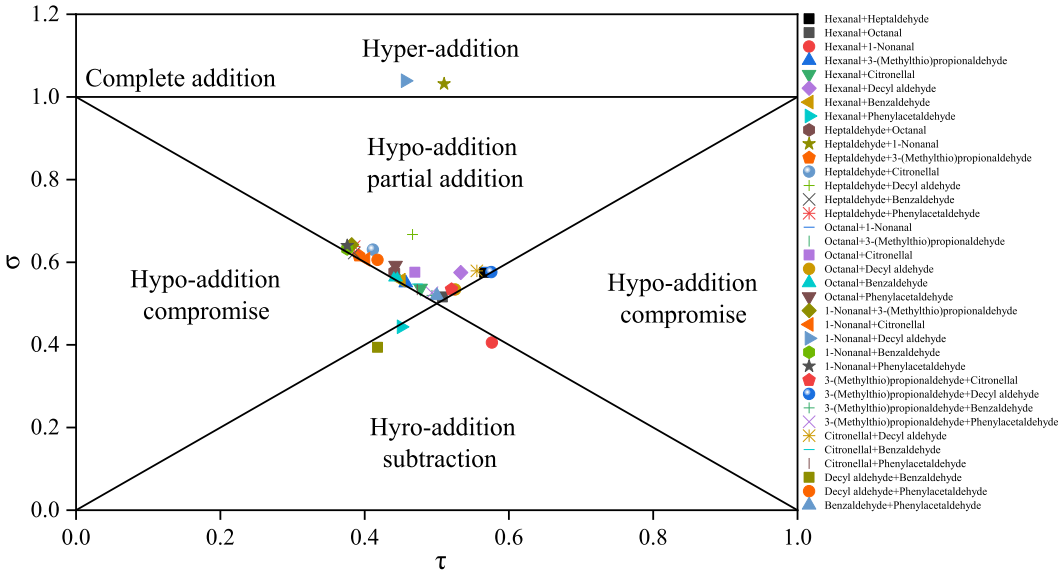


Fig. 3. The σ-τ plot representations of 36 pairs of binary mixtures.

3.4. Perceptual interactions between aldehydes with aldehyde recombination

3.4.1. S-curve method using Feller's additive model

To examine how the addition of certain key aldehydes would affect AR, the odor thresholds (Table 1b) of different aldehyde mixtures were measured, and the relationship between individual aldehydes and AR was further explored.

The AR thresholds obtained using the S-curve formula are shown in Table 1c. The thresholds of aldehyde recombinations 1 to 9 ranged from 51.28 μg/kg to 62.51 μg/kg. All of the regression coefficients (R^2) were over 0.95, indicating a good fit. The S-curves for the nine combinations (TAR) are presented in Fig. 4. The threshold ratios for combinations (a) to (i), namely (a) hexanal and AR1, (b) heptanal and AR2, (c) octanal and AR3, (d) 1-nonanal and AR4, (e) 3-(methylthio)propanal and AR5, (f) citronellal and AR6, (g) decyl aldehyde and AR7, (h) benzaldehyde and AR8, and (i) phenylacetaldehyde and AR9, were 0.70, 0.72, 0.77, 0.73 0.85, 0.73, 0.79, 0.72 and 0.78, respectively, indicating their

Table 1c
The threshold determination of aldehyde reconstitution.

No	AR [a]	log odor threshold	function steepness	log concentration	odor threshold (μg/kg)	R^2 [b]
1	AR1	1.74	0.24	1.74	55.05	0.9612
2	AR2	1.71	0.30	1.71	51.28	0.9715
3	AR3	1.74	0.24	1.74	54.77	0.9612
4	AR4	1.77	0.18	1.77	58.74	0.9802
5	AR5	1.80	0.32	1.80	62.51	0.9525
6	AR6	1.77	0.26	1.77	59.30	0.9567
7	AR7	1.75	0.23	1.75	56.60	0.9583
8	AR8	1.74	0.32	1.74	55.38	0.9522
9	AR9	1.74	0.35	1.74	54.99	0.9656

[a] AR, aldehyde reconstitution.
[b] R^2, goodness of fit.

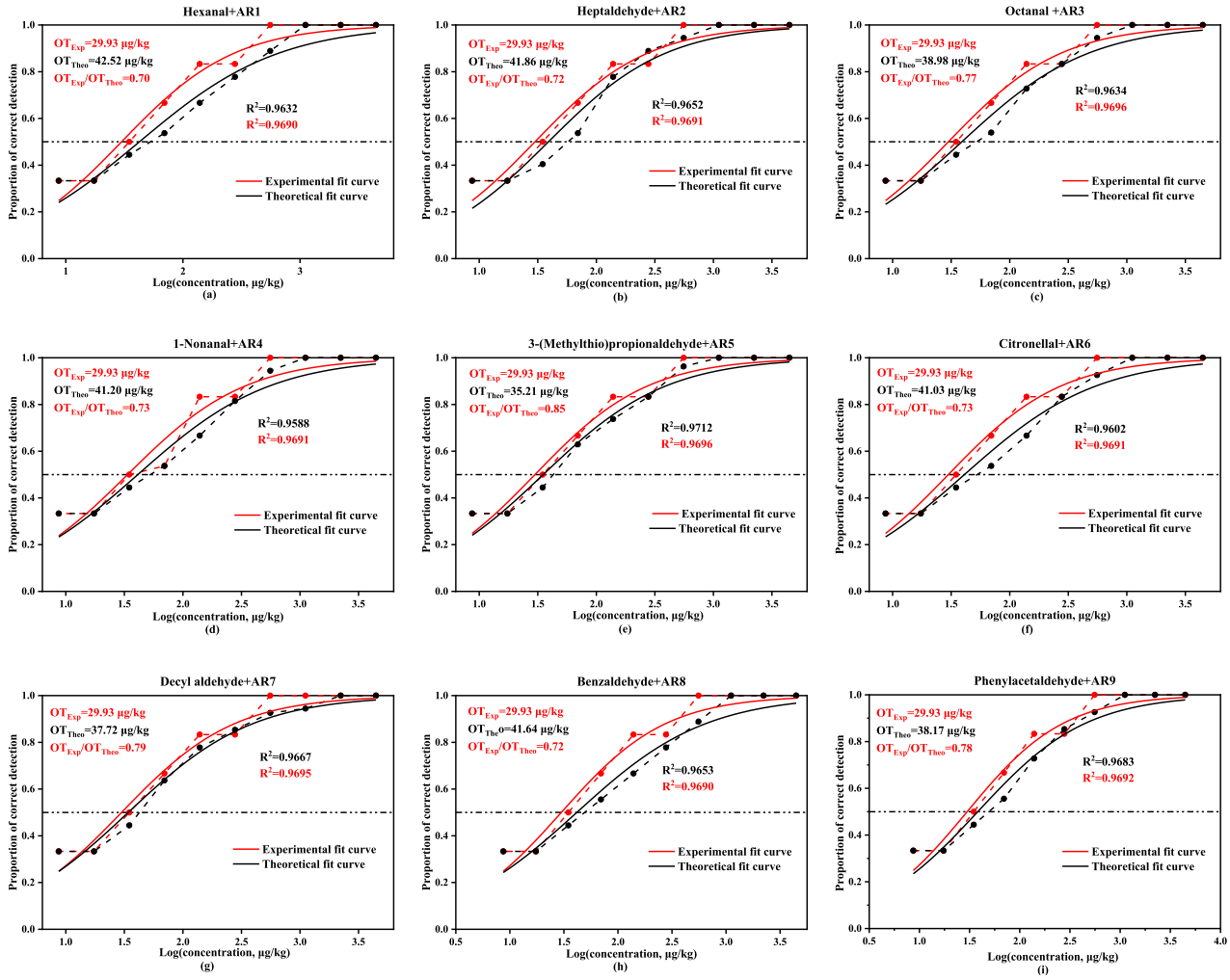


Fig. 4. Perceptual interactions between 9 key aldehydes and aldehyde reconstitution: (a) Hexanal and AR1, (b) Heptaldehyde and AR2, (c) Octanal and AR3, (d) 1-Nonanal and AR4, (e) 3-(Methylthio)propionaldehyde and AR5, (f) Citronellal and AR6, (g) Decyl aldehyde and AR7, (h) Benzaldehyde and AR8, and (i) Phenylacetaldehyde and AR9. AR, aldehyde reconstitution. OT, odor threshold. R^2, goodness of fit. The curves are drawn according to S-curves.

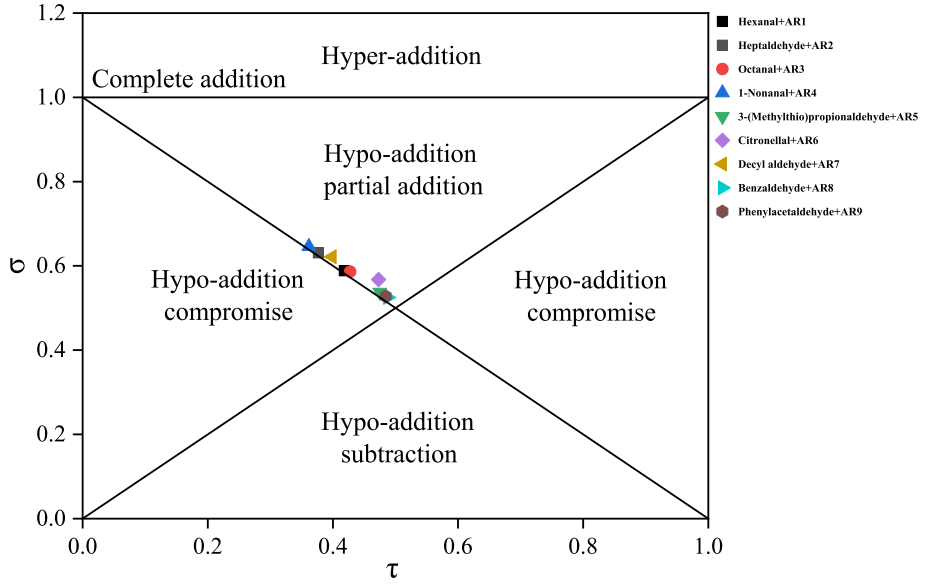


Fig. 5. The σ-τ plot representations of 9 aldehydes and aldehyde reconstitution.

additive effects. Combination (a) had the lowest threshold ratio (R = 0.70) of these combinations, indicating that the addition of hexanal could maximize the enhancement of the aroma intensity in AR. Contrarily, combination (e) showed the highest threshold ratio (R = 0.85), indicating that 3-(methylthio) propionaldehyde contributed little to overall aroma intensity. The TAR odor thresholds were all lower than those of AR, all of which were 29.93 μg/kg, suggesting that the addition of aldehydes lowered the odor thresholds of AR, possibly due to the interactions of the aldehydes with other components. This concurs with the conclusion reached by Zhu, Niu and Xiao (2021), who found that the aroma reconstitution thresholds decreased significantly after the addition of eight compounds, which demonstrated their contribution to the overall aroma of Laoshan green tea.

3.4.2. σ-τ plot method

To further understand the effect of individual aldehydes on AR aroma intensity in Kung Pao Chicken, the perceived interactions in different intensities of aldehyde mixtures were investigated using the σ-τ plot method.

As shown in Fig. 5, all data points of the mixtures were located in the region of an additive effect. The total intensities of the individual components were higher than those of the mixtures, and the intensities of the mixtures were greater than the maximum values of individual aroma intensities, indicating that the addition of the nine key aldehydes increased the aroma intensity of AR. These results were fully consistent and mutually verifiable with the conclusions of the S-curve method. Specifically, the σ values for the nine mixtures were 0.59, 0.63, 0.59, 0.65, 0.54, 0.57, 0.62, 0.53 and 0.53, respectively, indicating that additive effects occurred to varying degrees. The greatest impact on the aroma intensity of AR was caused by the addition of 1-nonanal (σ = 0.65), while the addition of benzaldehyde (σ = 0.53) had a weaker effect, which may have been due to the low OAV of benzaldehyde or the low level of interactions between benzaldehyde and other compounds in AR.

One possible explanation for the absence of other effects in the experiment is that additive effects are more commonly observed, with other types of interactions occurring less frequently. Masking effects, for example, can occur when the pleasantness of two components differs significantly (Ma, Tang, Xu, & Thomas-Danguin, 2021), while synergistic effects occur when at least one component is barely detectable or is present at a low intensity (Ferreira, 2012). However, additive effects can happen for numerous reasons because of the variety of factors influencing the interactions between aroma compounds, including physical factors (such as functional group types, molecular sizes and volatility) and chemical factors (such as hydrophobicity, van der Waals forces and hydrogen bonding) (Lorrain, Tempere, Iturmendi, Moine, de Revel, & Teissedre, 2013; Tian, Xu, Sun, Chen, & Yu, 2020).

4. Conclusions

Various interactions were observed in the binary mixtures of aldehydes in Kung Pao Chicken. All the combinations showed either additive or synergistic effects, except the combinations of hexanal and 1-nonanal, hexanal and phenylacetaldehyde, and decyl aldehyde and benzaldehyde, which exhibited masking effects. All nine aldehydes were found to exert aroma additive effects on AR, and their addition enhanced flavor intensity. The effect of interactions on flavor perception was significantly linked to the influence of matrix components on the volatility of aldehydes. It was also noted that additive effects occurred typically when the measured threshold was below the theoretical threshold. Masking effects usually occurred as the second-most likely scenario, while synergistic effects were rarely observed. These results have implications for both fundamental and applied research, as this study has uncovered the perceptual interaction law of aroma in Kung Pao Chicken, thereby providing new insights into aroma interactions in meat products. Additionally, the experimental results have practical-related implications for improving the aroma quality and overall aroma characteristics of Kung Pao Chicken. Future research should explore the mechanisms and influencing factors of aroma compound interactions in depth, such as the intermolecular forces affecting compound volatility, which will contribute to a more comprehensive understanding of the laws of interactions between aroma molecules.

Ethical statement

In this study, all study participants provided informed consent, and the study design was approved by the ethics review board of Xihua University. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these.

CRediT authorship contribution statement

Shengchao Lin: Investigation, Methodology, Writing – review & editing. **Na Li:** Investigation. **Xingtao Zhou:** Methodology. **Songling Li:** Investigation. **Aiping Yang:** Investigation. **Jiao Zhou:** Investigation. **Ping Liu:** Conceptualization, Formal analysis, Funding acquisition, Supervision.

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.

Data availability

Data will be made available on request.

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