



HAL
open science

Pleasantness of Binary Odor Mixtures: Rules and Prediction

Yue Ma, Ke Tang, Thierry Thomas-Danguin, Yan Xu

► **To cite this version:**

Yue Ma, Ke Tang, Thierry Thomas-Danguin, Yan Xu. Pleasantness of Binary Odor Mixtures: Rules and Prediction. *Chemical Senses*, 2020, 45 (4), pp.303-311. 10.1093/chemse/bjaa020 . hal-02880526

HAL Id: hal-02880526

<https://hal.inrae.fr/hal-02880526v1>

Submitted on 25 Jun 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Pleasantness of binary odor mixtures: rules and prediction

Yue Ma,^{†‡} Ke Tang,[†] Thierry Thomas-Danguin,^{*‡} Yan Xu ^{*†}

[†] School of Biotechnology, Jiangnan University, 1800 Lihu Avenue, Wuxi, Jiangsu 214122, People's Republic of China.

[‡] Centre des Sciences du Goût et de l'Alimentation, INRAE, CNRS, AgroSup Dijon, Université Bourgogne Franche-Comté, Dijon, France.

* To whom correspondence should be addressed:

Dr. Thierry Thomas-Danguin (Tel: +33 380 693084; Fax: +33 380 693227);

E-mail: thierry.thomas-danguin@inrae.fr

Prof. Yan Xu. (Tel: +86 510 85918197; Fax: +86 510 85918201);

E-mail: yxu@jiangnan.edu.cn

Accepted Manuscript

1 **Abstract**

2 Pleasantness is a major dimension of odor percepts. While naturally encountered odors rely on
3 mixtures of odorants, few studies have investigated the rules underlying the perceived pleasantness
4 of odor mixtures. To address this issue, a set of 222 binary mixtures based on a set of 72 odorants
5 were rated by a panel of 30 participants for odor intensity and pleasantness. In most cases, the
6 pleasantness of the binary mixtures was driven by the pleasantness and intensity of its components.
7 Nevertheless, a significant pleasantness partial addition was observed in six binary mixtures
8 consisting of two components with similar pleasantness ratings. A mathematical model, involving
9 the pleasantness of the components as well as τ -values reflecting components' odor intensity, was
10 applied to predict mixture pleasantness. Using this model, the pleasantness of mixtures including
11 two components with contrasted intensity and pleasantness could be efficiently predicted at the
12 panel level ($R^2 > 0.80$, $RMSE < 0.67$).

13
14 **Keywords: odorants, binary mixtures, hedonic value, prediction**

15

16 **Introduction**

17 The main features of odor percepts include odor intensity, odor quality, and odor pleasantness. It
18 has been suggested that the most important one is pleasantness (hedonic dimension or valence)
19 (Block, 2018; Rolls, Kringelbach, & de Araujo, 2003; Wise, Olsson, & Cain, 2000). In particular,
20 when a wide range of odors are assessed at a similar odor intensity, the hedonic dimension is the
21 most salient (Zarzo, 2008). The pleasantness of an odor not only affects our judgment but also
22 causes changes in individual physiological parameters. Exposure to odors with different
23 pleasantness levels can modify heart rate, skin conductance, and skin temperature (He, Boesveldt,
24 de Graaf, & de Wijk, 2014). Odor pleasantness is determined by many factors, including the
25 molecular structure (Khan et al., 2007), odor quality (Kermen et al., 2011) and odor intensity (Doty,
26 1975) of the odorant; but also individual features, such as genetic (Keller, Zhuang, Chi, Vosshall, &
27 Matsunami, 2007) and cognitive factors, aging (Konstantinidis, Hummel, & Larsson, 2006), culture
28 (Ayabe-Kanamura et al., 1998; Seo et al., 2011) and physiological status (Rouby, Pouliot, &
29 Bensafi, 2009); and temporary environmental factors, such as visual stimuli (Hummel et al., 2017).

30 Most olfactory stimulation naturally occurring are mixtures of odorants (Thomas-Danguin et al.,
31 2014). In food for instance, odor stimuli consists of 3 to 40 genuine key odorants whose
32 composition and concentration ratios vary (Dunkel et al., 2014). In that case, perceptual
33 interactions inducing e.g. masking or synergy add another level of complexity in food flavor
34 understanding (Burseg & de Jong, 2009; Escudero, Campo, Farina, Cacho, & Ferreira, 2007; Lytra,
35 Tempere, de Revel, & Barbe, 2012; Ma, Tang, Xu, & Li, 2017; Thomas-Danguin et al., 2014).
36 Factors including the relative intensities of odorants, mixture complexity, component salience,
37 trigeminal interactions (Walliczek-Dworschak et al., 2018), chemical structure, and possible
38 peripheral interactions can influence odor mixture perception (Kay, Lowry, & Jacobs, 2003). The

39 analysis of binary mixture perception is the first step in understanding the perception of odor
40 mixtures.

41 Attempts to explain the underlying principles of binary mixture perception have mainly
42 investigated odor quality and intensity (Atanasova et al., 2005; Berglund & Olsson, 1993; Ferreira,
43 2012a, 2012b; Laing, Panhuber, Willcox, & Pittman, 1984; Laing & Willcox, 1983; McNamara,
44 Magidson, & Linster, 2007; Miyazawa, Gallagher, Preti, & Wise, 2009; Thomas-Danguin &
45 Chastrette, 2002). Nevertheless, at present, only a few studies have attempted to investigate the
46 pleasantness of binary mixtures. In the odor mixture literature, it is widely accepted that the
47 pleasantness of a binary mixture tends to be an intermediate value between the pleasantness values
48 of its components (Moskowitz & Barbe, 1977; Spence & Guilford, 1933) and that the perceived
49 pleasantness is highly dependent on intensity (Laing, Eddy, & Best, 1994; Lawless, 1977). H.
50 Lawless studied two binary mixtures, each composed of a pleasant and an unpleasant odorant at
51 various concentration levels. He proposed a prediction model for the pleasantness of binary
52 mixtures from the pleasantness of their constituents, weighted by their intensity (Lawless, 1977).
53 However, until now, only a limited number of binary odor mixtures have been evaluated with
54 regard to their pleasantness, calling into question the applicability of these rules in a wider range of
55 odorants. Indeed, in natural products, a large range of odorants that span stimulus space have been
56 identified. For instance, a total of 226 key food odorants were identified in 227 food samples
57 (Dunkel et al., 2014).

58 The latest available research on the pleasantness of binary mixtures was conducted by Lapid et al.
59 (Lapid, Harel, & Sobel, 2008). By ranking the pleasantness and intensity of 5 distinct binary
60 mixtures constructed with different ratios of the separate constituent odors, a prediction model with

61 good performance was established (Lapid et al., 2008). This model proposed the possible prediction
62 of the pleasantness of binary mixtures from the pleasantness of their separate constituents weighted
63 by their respective perceived intensities. Interestingly, in this study, the authors observed a partial
64 addition effect (Ferreira, 2012a; Thomas-Danguin et al., 2014) for the mixture of L-carvone and
65 linalool at the 50–50% concentration ratio, meaning that the pleasantness of the mixture was higher
66 than the pleasantness of the individual constituents (Lapid et al., 2008). These results underlined the
67 key role of odor intensity in pleasantness and suggested that mixtures made of two components with
68 similar intensities might show interesting pleasantness effects.

69 The aim of the present study was twofold. First, we investigated the pleasantness of a large set of
70 binary mixtures (222 mixtures) based on a set of 72 odorants that occur in natural products,
71 especially food products. The odorants were selected to span the stimulus space and to cover the
72 entire range of pleasantness. The mixtures were designed to combine odorants with similar
73 perceived intensities because we expected to observe the most interesting patterns from mixture
74 interactions. Indeed, mixtures including a component with a high perceived intensity should have
75 pleasantness close to that of the most intense component. Second, we adapted a mathematical model
76 and then applied it to our dataset to predict the pleasantness of the 222 binary mixtures.

78 **Materials and methods**

79 **Subjects**

80 One hundred twenty-five healthy subjects between the ages of 18 and 25 were recruited from
81 Jiangnan University. Sixty-six of these subjects went through screening tests that evaluated their
82 performance in discriminating between different odors qualities and different odor intensity levels,

83 as well as their performance in logic scaling. To test their ability to evaluate odor quality and
84 intensity, six samples comprising three different odorants at two concentration levels were
85 provided. The subjects needed to sort these six samples into three groups based on their odor quality
86 similarity and then rank the odor intensity of the samples within the same group. Only the subjects
87 who answered both parts correctly, i.e., gathered the samples with the same odor quality into a
88 group and then correctly ranked the odor intensity within the groups, were selected for the
89 experiment. To further test subjects' scaling abilities, we provided six pictures proposed by
90 Meilgaard et al. (Meilgaard, Carr, & Civille, 2006). These pictures had different shadowed areas,
91 and subjects had to evaluate the approximate area using a linear scale. The values given by subjects
92 were compared to the correct values, and only subjects who gave substantially incorrect ratings
93 were not selected.

94 All subjects provided informed consent in line with the Helsinki Declaration, and six subjects
95 quit after the training session, leaving 60 subjects (41 female) to participate in the experiment.
96 Before the main experiment, subjects participated in 2 training sessions that aimed to provide
97 standards for intensity scale use (see below). During the main experiment, not all the subjects
98 evaluated all the samples (hereafter called trials because each trial included 3 odorized vials); for a
99 given sample, 30 subjects performed the evaluation. Trials were randomly assigned to the subjects,
100 who participated in a minimum of 3 and a maximum of 15 sensory sessions, with a maximum of 3
101 sessions occurring per week. During a session, participants evaluated 8 to 10 trials. Subjects were
102 paid for their participation.

103

104 **Stimuli**

105 Odorants occurring in natural products were the focus. To select these odorants, we included the
106 226 key food odorants (KFOs) identified in Dunkel et al. (Dunkel et al., 2014) and added 548
107 different odorants collected in the *Flavornet* database (<http://www.flavornet.org/>). For each of the
108 774 odorants we obtained circa 4000 physicochemical descriptors using the Dragon[®] software
109 (Talete, Milan, Italy). We finally selected 72 odorants (Supplementary Table 1) that covered the
110 physicochemical space (Weiss et al., 2012) and were easily available from providers. Most odorants
111 were purchased from Sigma-Aldrich China Co. (Shanghai, China) in the highest available purity,
112 except for *p*-anisaldehyde (obtained from Fluka) and 3-mercaptopentanol (obtained from ACROS
113 Organics). Ultimately, 198 different binary odor mixtures (Supplementary Table 2), plus 24
114 duplicated binary odor mixtures, made from the 72 odorants were designed for the experiments
115 based on their odor characteristics.

116 **Equal-intensity stimuli**

117 All odorants were diluted with odorless solvents which were 1,2-propanediol, or mineral oil or
118 deionized distilled water depending on odorant solubility. To avoid large differences in intensity
119 and to keep it in a narrow range for all samples, odorants were first diluted to a point approximately
120 equal to the odor intensity of ethyl 2-methylbutyrate at a concentration of 3.9 g/L, as estimated by
121 experienced lab members. Then, we prepared a set of solutions of odorants varying around the
122 obtained concentration. These solutions were presented to 6 subjects who did not participate in the
123 main experiment and who were instructed to provide a number between 0 and 7 reflecting the
124 solution odor intensity. For each odorant, the final concentration (Supplementary Table 1) was set
125 to match similar intensity following the procedure described in Weiss et al. (Weiss et al., 2012).

126 **Sample preparation**

127 To prevent the formation of novel chemicals in the mixtures, odorants were not mixed in the
128 liquid phase. For the unmixed odor samples, 200 μL of diluted stimulus was poured onto a 0.1 g
129 cotton ball and placed in a 20 mL brown glass bottle. For the binary mixtures, 200 μL of each
130 stimulus was poured onto separate sides of the 0.1 g cotton ball, such that the two odorants' vapors
131 alone mixed in the glass bottle headspace. All of the stimuli were fully absorbed by the cotton ball.
132 All samples were prepared one day before the sensory session and stored at room temperature
133 (24°C).

134 **General procedures**

135 The data presented in this study include 33,300 psychophysical single evaluations collected from
136 fifteen sessions across three months (Figure 1). Before the formal experiment, we began with two
137 training sessions. The first session determined the standard odor references to be used in the
138 experiment. Ethyl 2-methylbutyrate and linalool were selected as reference odorants because the
139 majority of panelists did not object to sniff it frequently, and because their corresponding odors
140 (fruity-green-apple and floral-citrus-lavender respectively) were rather familiar to the participants,
141 which might have helped them to memorize. To determine the standard intensity of these
142 references, we gave participants ethyl 2-methylbutyrate (1.8 g/L) and linalool (10.7 g/L) and asked
143 them to rate the intensity of these two samples. We asked them to evaluate ethyl 2-methylbutyrate
144 first, and then, they need to evaluate the intensity of linalool by comparing the intensity of linalool
145 with the intensity of ethyl 2-methylbutyrate. If the intensity of linalool smelled twice as strong as
146 ethyl 2-methylbutyrate, its intensity was marked twice the distance from zero as the position of
147 ethyl 2-methylbutyrate. The standard intensity was obtained by calculating the mean value of these

148 ratings across all subjects. The intensities of standard I (ethyl 2-methylbutyrate) and standard II
149 (linalool) were finally anchored as 3.0 and 7.0, respectively. The second session introduced the odor
150 evaluation procedures. During this session, the two standards were provided to the subjects, and
151 they were told that they had to rate the perceived intensity of the samples presented during the
152 formal sessions using the anchor intensities of the two standards.

153 In the formal sessions, a total of 222 trials, among which 24 were duplicated trials, were
154 evaluated (Figure 1). Each session in the formal experiment comprised 14 to 15 trials, and each trial
155 included three stimuli: two stimuli were single odorants, and the third stimulus was a binary
156 mixture of these odorants. In each trial, all the unmixed odor samples were coded by three random
157 digits, and the binary mixture sample was coded by its trial number. The order of the presentation of
158 the two unmixed odors was counterbalanced for each trial. Subjects were given a rest of 45 seconds
159 between each stimulus. Each trial was presented to subjects in a random order, and one trial was
160 evaluated by a maximum of 30 subjects.

161 Each session included three parts. The first part consisted of a hedonic evaluation, and the last
162 two parts consisted of intensity evaluations. During the hedonic evaluation, subjects had to mark off
163 distance on a visual analog scale 100-mm in length (Figure 1). For the intensity evaluations, in
164 order to get the panelists used to the scale in a similar way across the range of intensity, an adjusted
165 explicit anchoring scale was used by marking the position of standard I and standard II. The two
166 standards were determined in the training session, and were presented in the first two sessions to
167 help the subjects rate odor intensity. This kind of anchoring scale with reference standards has a
168 long history in texture analysis, which might generate more reliable sensory data by reducing the
169 variability among panelists both in evaluation procedures and individual judgments, as well as

170 within panelists in replicated assessments (Muñoz, 1986). Subjects had to mark off distance on the
171 visual analog scale according to the perceptual anchors. If the stimulus smelled twice as strong as
172 the standard, its intensity was marked twice the distance from zero as the standard position. If the
173 test stimulus smelled half as strong as the standard, its intensity was marked half the distance, and
174 so on (Figure 1). In the second part of the intensity evaluation session, subjects had to evaluate the
175 intensity of the unmixed components perceived in the binary mixture and whether they could
176 perceive a new odor in the mixture (data not shown).

177 **Data processing**

178 Psychophysical data obtained from the scales were transformed into numerical values. All the
179 scores within the range of the scale were translated to a value between 0.0 and 10.0. Statistical
180 analyses were performed with R software (version 3.5.3).

181 Panel performance was checked through principal component analysis (PCA). Nonparametric
182 Mixed Effects ANOVA was applied to test the repeatability of 24 duplicated trials for each intensity
183 variable using the *lmer* and *glmer* functions from the *lme4* package (Bates, Mächler, Bolker, &
184 Walker, 2014). The subject effect and trial effect were set as random factors. Differences between
185 trials were analyzed using an unpaired two-sample Wilcoxon test using the *wilcox.test* function
186 from the *ddply* package (Wickham, 2011). The averages across subjects of the intensity or
187 pleasantness of each odorant were compared to the mean values across odorants using unpaired
188 Wilcoxon test from the *ggpubr* package (Kassambara, 2019). The difference between odor intensity
189 (resp. pleasantness) of a binary mixture and its two components in each trial was analyzed using a
190 paired Wilcoxon test (*wilcox.test* function). Bonferroni correction was applied to account for
191 multiple testing when necessary.

192 The Tau-based model involving the τ -value, which reflects the relative proportion of the perceived
193 intensity of odor A or odor B to the sum of their intensities (Patte & Laffort, 1979), was applied to
194 predict the binary mixture pleasantness.

$$P_{AB} = \tau_A P_A + \tau_B P_B$$

$$\tau_A = \frac{I_A}{I_A + I_B} \text{ or } \tau_B = \frac{I_B}{I_A + I_B}$$

195 This model was equivalent to the intensity weights model proposed by Lapid et al. (Lapid et al.,
196 2008). The performance of this prediction model was tested by computing the prediction error Root
197 Mean Squared Error (*RMSE*) and the R-square (R^2) between experimental and predicted values.

198 This model was applied to predict the mixture odor pleasantness at *panel* level as well as
199 *individual* level. In the *panel* approach, a single pleasantness value was predicted for a given
200 mixture, while in the *individual* approach, a pleasantness value was predicted for each subject for a
201 given mixture. In addition, for the *panel* approach, predicted pleasantness was calculated using
202 either the average pleasantness across trials and mean τ -value of the 2 components (*mean* condition,
203 Equation 1) or using the average pleasantness across subjects and τ -values of each trial (*trial*
204 condition, Equation 2).

205 $P_{AB_mean} = \tau_{A_mean} P_{A_mean} + \tau_{B_mean} P_{B_mean}$ Equation 1

206 $P_{AB_trial} = \tau_{A_trial} P_{A_trial} + \tau_{B_trial} P_{B_trial}$ Equation 2

207 For example, ethyl 2-methylbutyrate is an odorant that was used in 29 trials. In the *mean*
208 condition of the *panel* approach, a single value of pleasantness and a single value of τ were
209 calculated and used to predict the pleasantness of all the mixtures including this odorant. In
210 contrast, in the *trial* condition of the *panel* approach, one average value of pleasantness and one τ

211 value across subjects were calculated for each trial to predict one value of mixture pleasantness per
212 trial.

213 In the *individual* approach, we also considered the two conditions *mean* and *trial*. Thus, predicted
214 pleasantness was calculated for each subject using either the average pleasantness across trials and
215 mean τ -value of the 2 components (*mean* condition, Equation 3) or using the pleasantness value and
216 τ -value from a given subject on each trial (*trial* condition, Equation 4).

$$217 P_{AB_subject} = \tau_{A_mean/subject} P_{A_mean/subject} + \tau_{B_mean/subject} P_{B_mean/subject} \text{ Equation 3}$$

$$218 P_{AB_subject} =$$

$$219 \tau_{A_subject\prime value / trial} P_{A_subject\prime value / trial} + \tau_{B_subject\prime value / trial} P_{B_subject\prime value / trial} \text{ Equation}$$

220 4

221 For example, for ethyl 2-methylbutyrate in the *mean* condition of the *individual* approach, an
222 individual value of pleasantness and τ was calculated across trials and was used to predict the
223 individual mean pleasantness of mixtures including this odorant, whereas in the *trial* condition of
224 the *individual* approach, one value of pleasantness and τ was calculated per trial for each subject.

225 In addition to the Tau-based model (intensity weights model), the squared model and the sin
226 model (Lapid et al., 2008) were applied to predict the binary mixture pleasantness. Using the
227 *cor.test* function, the prediction performances of the three models were compared based on the
228 Pearson's product moment correlation coefficient between predicted and experimental pleasantness
229 and the 95 percent confidence interval on this correlation coefficient. The formula of each model
230 and the correlation results were provided in Supplement Table 3. The results showed that there was
231 no significant difference between the three models since there is an overlap of the 95 percent

232 confidence interval within each prediction approach/condition. Hereafter, only the simplest Tau-
233 based model was considered.

234

235 **Results and Discussion**

236 **Panel performance and repeatability**

237 The subjects' overall performance and coherence were checked using PCA on the raw data. The
238 PCA map of individuals for the first 2 dimensions, explaining 16.7% of the total variance, is
239 reported in Supplementary Figure 1. We checked the individual results from the subjects outside of
240 the central cloud for the different variables more in depth, and we did not identify any systematic
241 outliers. Therefore, all the data were kept for further analyses.

242 Nonparametric Mixed Effects ANOVA was applied to test repeatability using the 24 duplicated
243 trials for each attribute. Variables included the intensity of odor A (I_A) or odor B (I_B), the
244 pleasantness of odor A (P_A) or odor B (P_B), and the pleasantness of the binary mixture (P_{AB}). The
245 results indicated no significant repetition effects ($p > 0.05$), except for the pleasantness of odor A
246 (P_A , $p < 0.001$). By checking the repeatability of attributes P_A for each repeated trial, only the means
247 of Trial 36 (ethyl 2-methylbutyrate, Supplementary Table 2) was found to be significantly different
248 between the replicates (Wilcoxon-test with Bonferroni correction). Ethyl 2-methylbutyrate was used
249 29 times in the whole experiment (Supplementary Table 1, and Supplementary Figure 2); thus, the
250 pleasantness rating might have evolved as a result of increasing familiarity with the odor of this
251 compound. Although the pleasantness of ethyl 2-methylbutyrate might have been overrated at the
252 end of the pleasantness evaluation, the statistical assessment showed that the panel could rate odor

253 intensity and pleasantness consistently and consensually in most cases and that the psychophysical
254 data were statistically reliable.

255 **Binary odor pleasantness perception**

256 The mean intensity and pleasantness of each odorant were calculated across subjects in all trials
257 (Figure 2). Uncorrected unpaired Wilcoxon test was used to test the difference between the intensity
258 of each odorant and the mean intensity value across odorants. Although we tried to provide stimuli
259 that had similar intensities (preliminary test with external panel of six subjects), the results showed
260 that there were 19 out of 72 odorants whose odor intensity was significantly different from the mean
261 value ($p < 0.001$). Among these odorants, ethyl octanoate, *o*-aminoacetophenone, ethyl valerate, *p*-
262 cresol, γ -undecalactone, butanal, pentanal, phenylethylthiol and benzaldehyde had intensities that
263 were significantly higher than the mean intensity ($p < 0.001$), with intensities ranging from 6.53 to
264 7.71, while the intensities of ethyl laurate, undecanaldehyde, 2-pentanone, vanillin, γ -butyrolactone,
265 eugenol, ethyl 3-(methylsulfanyl)propanoate, nerol oxide, carveol, geraniol and isoeugenol were
266 significantly lower than the mean intensity ($p < 0.001$), with intensities ranging from 3.68 to 5.15
267 (Supplementary Figure 3). Uncorrected unpaired Wilcoxon test was also used to test the difference
268 between the pleasantness value of each odorant and the mean value, and there were 19 odorants
269 whose odor pleasantness was significantly different from the mean value ($p < 0.001$)
270 (Supplementary Figure 3).

271 Uncorrected paired Wilcoxon test was used to evaluate the difference in intensity and
272 pleasantness between the two components of each of the 198 different binary odor samples (trials).
273 As a result, four groups of trials were considered. First, group E, comprising 50 trials, showed no
274 significant difference in either intensity or pleasantness ($p < 0.05$); group I, which included 52

275 trials, showed a significant difference in intensity only ($p < 0.05$); group P, comprising 39 trials,
276 showed a significant difference in pleasantness only ($p < 0.05$); and finally, group IP, comprising
277 the remaining 57 trials, showed a significant difference in both intensity and pleasantness ($p < 0.05$)
278 was obtained (Supplementary Table 2).

279 The results of pleasantness rating of the 198 binary odor mixtures showed that, in most cases,
280 mixture pleasantness was in-between pleasantness of the unmixed odorants (Figure 3), and that
281 mixture pleasantness scores varied according to pleasantness and intensity scores of the unmixed
282 odorants. If the binary mixture consisted of two components with contrasted pleasantness and
283 intensity (group IP), the pleasantness of the binary mixture was generally closer to that of the
284 stronger odor component. For example, in the trial with ethyl valerate and *p*-cymene (Trial 2), the
285 pleasantness (5.39) and intensity (7.19) of ethyl valerate were higher than the pleasantness (4.06)
286 and intensity (5.21) of *p*-cymene, and the pleasantness of the binary odor (5.27) was closer to that of
287 ethyl valerate. In the trial with 1-heptanol and phenylethylthiol (Trial 12), the pleasantness of 1-
288 heptanol (4.58) was higher than that of phenylethylthiol (2.45), but its intensity (4.58) was weaker
289 than that of phenylethylthiol (7.43). The pleasantness of the binary odor (2.34) was almost the same
290 as that of phenylethylthiol. However, this pattern did not apply for all trials, such as that with γ -
291 heptalactone and diethyl acetal (Trial 150), vanillin and diethyl acetal (Trial 153) or ethyl 3-
292 methylbutanoate and ethyl isobutyrate (Trial 160). In the trial with vanillin and diethyl acetal, there
293 were significant differences in both the intensity and pleasantness of these two odorants; the
294 intensity of vanillin (4.03) was weaker than that of diethyl acetal (5.40), but the pleasantness of the
295 binary odor (6.52) was closer to that of vanillin (6.48) than diethyl acetal (4.74). This phenomenon
296 might have resulted from perceptual interactions at the intensity level. For instance, a masking
297 effect caused by vanillin could reduce the intensity of the odor of diethyl acetal in the mixture due

298 to the perceptual dominance of the vanillin odor quality (Atanasova et al., 2005), and therefore, the
299 pleasantness of the mixture would be closer to that of vanillin alone.

300 If the binary odor mixture included two odorants with contrasted pleasantness but almost the
301 same intensity (group P), the pleasantness of the binary mixture was generally near the mean
302 pleasantness or was closer to the lower pleasantness value of the two odors. This phenomenon was
303 observed in most trials, except for those with 2-octanone and ethyl butyrate (Trial 121), hexyl
304 hexanoate and geranyl acetate (Trial 171), geraniol and ethyl butyrate (Trial 183), and ethyl
305 butyrate and hexanal (Trial 198). In these four trials, the pleasantness of the binary mixture was
306 close to the highest pleasantness value of the two odors. This specific case might result from
307 perceptual interactions such as masking, synergy (Ferreira, 2012a) or perceptual dominance
308 (Atanasova et al., 2005), which may affect odor intensity and/or odor quality of the odor mixture
309 and consequently its pleasantness.

310 Overall, for mixtures including a pleasant and a less pleasant component, we observed, in most of
311 the cases, that the stronger constituent was more influential on the mixture's pleasantness than the
312 weaker one. This rule is in accordance with previous observations (Laing et al., 1994; Lapid et al.,
313 2008; Lawless, 1977; Moskowitz & Barbe, 1977; Spence & Guilford, 1933). Moreover, the weight
314 of this influence was stronger for unpleasant components, as previously reported (Lawless, 1977).
315 However, the special cases observed in group IP and group P also indicated that the pleasantness of
316 binary mixtures is driven by the intensity of each component perceived within the mixture rather
317 than by the intensity perceived out of the mixture. Indeed, mixing at least two odors can lead to
318 several quantitative and qualitative effects on the mixture odor (Berglund & Olsson, 1993) and/or
319 quality effects (e.g., perceptual dominance (Atanasova et al., 2005)) that further influence the odor

320 pleasantness of the mixture. These perceptual interactions can arise from several biochemical or
321 neurobiological interactions during all stages of olfactory information processing within the
322 olfactory system, from the periphery to the brain (Thomas-Danguin et al., 2014). As odor
323 pleasantness is believed to be partially innate, but also strongly shaped by experience and learning
324 (Prescott, Kim, & Kim, 2008), an odorant with higher recognition or carrying nutritious or
325 poisonous information might capture more attention in a binary mixture (White, Thomas-Danguin,
326 Olofsson, Zucco, & Prescott, 2020) and these factors might play an important role in the
327 pleasantness judgement of the binary mixture. Indeed, the attentional capture effect has been
328 highlighted in brain imaging studies using a binary odor mixture including a pleasant and an
329 unpleasant component (Grabenhorst, Rolls, & Margot, 2011; Grabenhorst, Rolls, Margot, da Silva,
330 & Velazco, 2007).

331 If the binary mixture consisting of two components with similar pleasantness (group I and group
332 E), the pleasantness of the binary mixture was, in most cases, the same as that of the components,
333 but we also observed several cases indicating partial addition. A partial addition effect means that
334 the pleasantness of the mixture is higher than the pleasantness of each component individually or
335 that the pleasantness of the mixture is lower than that of each component individually. In the latter
336 case, one can consider this effect as partial addition for unpleasantness. In our dataset, we observed
337 that there were 52 trials (26%) showing partial additive pleasantness, meaning that the pleasantness
338 of the binary mixtures was higher than either of its components, and 28 trials (14%) in which partial
339 additive unpleasantness occurred (e.g., the pleasantness of the mixture was lower than that of either
340 of its components). The statistical significance of the pleasantness partial addition effect for each
341 trial was tested by uncorrected paired samples Wilcoxon tests. If there were significant differences
342 between the pleasantness of each component (P_A or P_B) and the pleasantness of the mixture (P_{AB}),

343 and if the pleasantness of the mixture was lower than the sum of pleasantness score of each
344 component (P_A+P_B), we considered that the pleasantness partial addition effect was significant.
345 There were 6 trials with significant partial additive pleasantness: methyl octanoate and ethyl 2-
346 methylbutyrate (Trial 61, $p < 0.05$), ethyl octanoate and benzyl acetate (Trial 83, $p < 0.01$),
347 isoeugenol and γ -decalactone (Trial 188, $p < 0.05$), 1,8-cineole and ethyl valerate (Trial 196, $p <$
348 0.05), linalool and 2-octanone (Trial 206, $p < 0.01$), and eugenol and 2-octanone (Trial 217, $p <$
349 0.05) (Supplementary Table 2). Here, significant partial additive pleasantness was only observed in
350 five binary mixtures consisting of two components with similar pleasantness and intensity and in
351 one binary mixture consisting of two components with similar pleasantness but different intensity.
352 Significant partial additive pleasantness was observed in a mixture of *L*-carvone and linalool at a
353 50–50% concentration ratio in Lapid’s study (Lapid et al., 2008). It is interesting to consider that at
354 the 50–50% concentration ratio, the intensity and pleasantness of *L*-carvone and linalool were also
355 similar in the abovementioned study. Therefore, it is reasonable to propose that pleasantness partial
356 addition might tend to occur in mixtures with two components of similar pleasantness and similar
357 intensity. One speculation that can explain partial additive pleasantness would consider an additive
358 effect in the intensity of the mixture (Lapid et al., 2008), but the underlying principles of the effects
359 need to be investigated more in depth through a systematic study of more binary mixtures of that
360 kind.

361 There were 28 trials in which partial additive unpleasantness was observed, but none of them
362 were found to reach a statistically significant level. A study (Laing et al., 1994) investigated the
363 interactions between four sewage-related unpleasant odorants: hydrogen sulphide, isovaleric acid,
364 butanethiol, and skatole. In this research, the pleasantness of a mixture was lower than the
365 pleasantness of the individual (unmixed) components in most instances (Laing et al., 1994). Thus,

366 based on this result, we assumed that the unpleasantness of a mixture might be stronger than that of
367 the individual constituents if the binary mixture consists of two extremely unpleasant odorants. In
368 our dataset, several binary mixtures included two components with extremely unpleasant odors
369 (e.g., Trial 34, 40, 66, and 154). Nevertheless, the unpleasantness of these binary mixtures was not
370 stronger than that of the individual constituents. Another example of partial additive unpleasantness
371 was observed in the mixture of butanoic acid and phenylethyl alcohol, even though the effect was
372 not significant (Lapid et al., 2008). The author speculated that partial additive unpleasantness might
373 occur in cases in which at least one of the components shows a steep decline in pleasantness as a
374 function of its intensity and an increase in the intensity of the mixture above the intensity of its
375 constituents (Lapid et al., 2008).

376 **Pleasantness prediction**

377 A model based on the τ -value proposed by Patte and Laffort (Patte & Laffort, 1979) reflecting the
378 relative proportion of the perceived intensity of odor A or odor B in a mixture was applied to
379 predict the pleasantness of binary mixtures. This model was equivalent to the intensity weights
380 model one used by Lapid et al. (Lapid et al., 2008). This model was applied to predict mixture odor
381 pleasantness not only at the *panel* level but also at the *individual* level. In addition, for *panel* and
382 *individual* approaches, predicted pleasantness was calculated as a *mean* condition and as a *trial*
383 condition to check whether the differences in pleasantness and intensity that may arise for a given
384 pair of odors (i.e., within a *trial*) have an impact on the mixture pleasantness rating or, in contrast, if
385 pleasantness and intensity might be considered as properties of the compounds (i.e., *mean*)
386 regardless of the odor pair. The model performance was evaluated by computing the prediction
387 error *RMSE* and the R^2 . *RMSE* represents the average difference between the perceptual

388 pleasantness in trials and the predicted pleasantness by the model. The R^2 represents the correlation
389 between the perceptual pleasantness and the predicted pleasantness. The lower the $RMSE$ and the
390 higher the R^2 are, the better the model.

391 The performance of the model for the *panel* approach obtained for the *mean* condition and the
392 *trial* condition are shown in Figure 4a. In the *panel* approach, for all the trials in the *trial* condition,
393 the R^2 was 0.857, the prediction error $RMSE$ was 0.428, whereas in the *mean* condition, the R^2 was
394 0.732, and the prediction error $RMSE$ was 0.584, meaning that the prediction in the *trial* condition
395 was better than that in the *mean* condition. Then, the prediction model was used to predict the
396 pleasantness of the four trial groups we defined above (group E, group I, group IP, group P). The
397 results (Table 1) showed that in the *trial* condition, the prediction model performed quite well
398 regardless of the group ($R^2 > 0.80$). However, in the *mean* condition, only group IP obtained a high
399 R^2 value. This result showed that the model performance in predicting group IP was high, meaning
400 that the model based on the τ -value predicting the pleasantness of a binary mixture consisting of
401 two components with contrasted intensity and pleasantness performed quite well regardless of the
402 odor pair. For group I, in which components had contrasted intensity, the R^2 value was low, but the
403 prediction error $RMSE$ was also low; in this case, it is likely that only a few instances of poor
404 prediction might have been observed. For every group, especially for groups I, P and E, the model
405 performance in the *mean* condition was worse than that in the *trial* condition. This result suggests
406 that a context effect existed for specific combinations. The context effect, which implies that the
407 perception of one odorant is influenced by the other odorant in the pair, might be an influential
408 factor for pleasantness, especially for couples of odorants with similar odor pleasantness or
409 intensity. In the future, at the *panel* level, an improved prediction model for the pleasantness of
410 binary mixtures of two components with similar intensity or pleasantness must take into account the

411 context effect, for instance, considering specific chemical features or specific odor quality features
412 of the mixed odorants, to be able to account for additive effects.

413 This model was then used to determine whether the *individual* pleasantness of a given binary
414 odor can be predicted (Figure 4b). Compared with the prediction in the *panel* approach, the
415 predictions in the individual approach were relatively poor regardless of the condition (trial or the
416 mean) and regardless of the trial group (Table 3). The significant variance and poor predictive
417 performance of the model specified that predictions at an *individual* level are still a major challenge.
418 This difficulty might be due to the high interindividual variability in odor pleasantness (Lindqvist,
419 Hoglund, & Berglund, 2012), supported by individual genetic and cognitive differences. Indeed,
420 previous research has shown that genetic variation across the human olfactory receptor repertoire
421 alters odor perception in the intensity and pleasantness of a given odor (Keller et al., 2007; Trimmer
422 et al., 2019), and stimulus intensity, repeated exposure, sex and hormonal status, aging, emotional
423 status, and cultural background can all influence individual pleasantness ratings (Rouby et al.,
424 2009).

426 **Conclusions**

427 On the basis of a sample set of 198 different binary odor mixtures, we showed that when two
428 odorants are mixed, the pleasantness of the binary mixture follows different rules: 1) If two
429 odorants with significantly different intensity were mixed, in most cases, the pleasantness of the
430 binary mixture was closer to that of the strongest odor component. 2) If two odorants with similar
431 intensity but contrasted pleasantness were mixed, the pleasantness of binary mixture was generally
432 near the mean pleasantness or was closer to that of the odor with the lower pleasantness value. 3)

433 Partial additive pleasantness tended to occur in mixtures of two components with similar
434 pleasantness and intensity ratings. We highlighted that a model based on the τ -value predicting the
435 pleasantness of a binary mixture consisting of two components with contrasted or similar intensity
436 and pleasantness performed quite well regardless of the odor pair, whereas prediction at the
437 individual level was still a major challenge. In future studies, it would be interesting to use this
438 model to predict the pleasantness of larger mixtures, while considering them as a series of binary
439 mixtures.

440

441

Accepted Manuscript

442 **Funding**

443 This work was supported by the National Key R&D Program (2016YFD0400504), National
444 First-class Discipline Program of Light Industry Technology and Engineering (LITE 2018-12),
445 China Scholarship Council (201806790033), and Postgraduate Research & Practice Innovation
446 Program of Jiangsu Province (KYCX18_1788).

447 **Acknowledgments**

448 The authors are grateful to all the subjects for participating in the psychophysical experiment.

449

450

Accepted Manuscript

451 **References**

- 452 Atanasova, B., Thomas-Danguin, T., Chabanet, C., Langlois, D., Nicklaus, S., & Etievant, P. (2005).
453 Perceptual interactions in odour mixtures: odour quality in binary mixtures of woody and
454 fruity wine odorants. *Chem. Senses*, 30(3), 209-217. doi:10.1093/chemse/bji016
- 455 Ayabe-Kanamura, S., Schicker, I., Laska, M., Hudson, R., Distel, H., Kobayakawa, T., & Saito, S.
456 (1998). Differences in perception of everyday odors: a Japanese-German cross-cultural
457 study. *Chem. Senses*, 23(1), 31-38. doi:10.1093/chemse/23.1.31
- 458 Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using
459 lme4. *arXiv preprint arXiv*, 1406(5823).
- 460 Berglund, B., & Olsson, M. J. (1993). Odor-intensity interaction in binary and ternary mixtures.
461 *Percept. Psychophys.*, 53(5), 475-482. doi:10.3758/bf03205195
- 462 Block, E. (2018). Molecular basis of mammalian odor discrimination: a status report. *J. Agric. Food*
463 *Chem.*, 66(51), 13346-13366. doi:10.1021/acs.jafc.8b04471
- 464 Burseg, K., & de Jong, C. (2009). Application of the Olfactoscan method to study the ability of
465 saturated aldehydes in masking the odor of methional. *J. Agric. Food Chem.*, 57(19), 9086-
466 9090. doi:10.1021/jf9016866
- 467 Doty, R. L. (1975). An examination of relationships between the pleasantness, intensity, and
468 concentration of 10 odorous stimuli. *Percept. Psychophys.*, 17(5), 492-496.
- 469 Dunkel, A., Steinhaus, M., Kotthoff, M., Nowak, B., Krautwurst, D., Schieberle, P., & Hofmann, T.
470 (2014). Nature's chemical signatures in human olfaction: a foodborne perspective for future
471 biotechnology. *Angew. Chem.-Int. Edit.*, 53(28), 7124-7143. doi:10.1002/anie.201309508
- 472 Escudero, A., Campo, E., Farina, L., Cacho, J., & Ferreira, V. (2007). Analytical characterization of
473 the aroma of five premium red wines. Insights into the role of odor families and the concept

- 474 of fruitiness of wines. *Journal of agricultural and food chemistry*, 55(11), 4501-4510.
475 doi:10.1021/jf0636418
- 476 Ferreira, V. (2012a). Revisiting psychophysical work on the quantitative and qualitative odour
477 properties of simple odour mixtures: a flavour chemistry view. Part 1: intensity and
478 detectability. A review. *Flavour Frag. J.*, 27(2), 124-140. doi:10.1002/ffj.2090
- 479 Ferreira, V. (2012b). Revisiting psychophysical work on the quantitative and qualitative odour
480 properties of simple odour mixtures: a flavour chemistry view. Part 2: qualitative aspects. A
481 review. *Flavour Frag. J.*, 27(3), 201-215. doi:10.1002/ffj.2091
- 482 Grabenhorst, F., Rolls, E. T., & Margot, C. (2011). A hedonically complex odor mixture produces an
483 attentional capture effect in the brain. *Neuroimage*, 55(2), 832-843.
484 doi:10.1016/j.neuroimage.2010.12.023
- 485 Grabenhorst, F., Rolls, E. T., Margot, C., da Silva, M., & Velazco, M. I. (2007). How pleasant and
486 unpleasant stimuli combine in different brain regions: odor mixtures. *J. Neurosci.*, 27(49),
487 13532-13540. doi:10.1523/jneurosci.3337-07.2007
- 488 He, W., Boesveldt, S., de Graaf, C., & de Wijk, R. A. (2014). Dynamics of autonomic nervous
489 system responses and facial expressions to odors. *Front. Psychol.*, 5, 110.
490 doi:10.3389/fpsyg.2014.00110
- 491 Hummel, T., Fark, T., Baum, D., Warr, J., Hummel, C. B., & Schriever, V. A. (2017). The rewarding
492 effect of pictures with positive emotional connotation upon perception and processing of
493 pleasant odors-an fMRI study. *Front. Neuroanat.*, 11, 19. doi:10.3389/fnana.2017.00019
- 494 Kassambara, A. (2019). ggpubr: "ggplot2" based publication ready plots (Version R Package Version
495 0.2; 2018.).
- 496 Kay, L. M., Lowry, C. A., & Jacobs, H. A. (2003). Receptor contributions to configural and

497 elemental odor mixture perception. *Behav. Neurosci.*, *117*(5), 1108-1114. doi:10.1037/0735-
498 7044.117.5.1108

499 Keller, A., Zhuang, H. Y., Chi, Q. Y., Vosshall, L. B., & Matsunami, H. (2007). Genetic variation in
500 a human odorant receptor alters odour perception. *Nature*, *449*(7161), 468-472.
501 doi:10.1038/nature06162

502 Kermen, F., Chakirian, A., Sezille, C., Jousain, P., Le Goff, G., Ziesel, A., . . . Bensafi, M. (2011).
503 Molecular complexity determines the number of olfactory notes and the pleasantness of
504 smells. *Sci. Rep.*, *1*, 206. doi:10.1038/srep00206

505 Khan, R. M., Luk, C. H., Flinker, A., Aggarwal, A., Lapid, H., Haddad, R., & Sobel, N. (2007).
506 Predicting odor pleasantness from odorant structure: pleasantness as a reflection of the
507 physical world. *J. Neurosci.*, *27*(37), 10015-10023. doi:10.1523/JNEUROSCI.1158-07.2007

508 Konstantinidis, I., Hummel, T., & Larsson, M. (2006). Identification of unpleasant odors is
509 independent of age. *Arch. Clin. Neuropsychol.*, *21*(7), 615-621.
510 doi:10.1016/j.acn.2006.05.006

511 Laing, D. G., Eddy, A., & Best, D. J. (1994). Perceptual characteristics of binary, trinary, and
512 quaternary odor mixtures consisting of unpleasant constituents. *Physiol. Behav.*, *56*(1), 81-
513 93.

514 Laing, D. G., Panhuber, H., Willcox, M. E., & Pittman, E. A. (1984). Quality and intensity of binary
515 odor mixtures. *Physiol. Behav.*, *33*(2), 309-319. doi:10.1016/0031-9384(84)90118-5

516 Laing, D. G., & Willcox, M. E. (1983). Perception of components in binary odor mixtures. *Chem.*
517 *Senses*, *7*(3-4), 249-264. doi:10.1093/chemse/7.3-4.249

518 Lapid, H., Harel, D., & Sobel, N. (2008). Prediction models for the pleasantness of binary mixtures
519 in olfaction. *Chem. Senses*, *33*(7), 599-609. doi:10.1093/chemse/bjn026

- 520 Lawless, H. T. (1977). The pleasantness of mixtures in taste and olfaction. *Sensory Processes, 1*,
521 227-237.
- 522 Lindqvist, A., Hoglund, A., & Berglund, B. (2012). The role of odour quality in the perception of
523 binary and higher-order mixtures. *Perception, 41*(11), 1373-1391. doi:10.1068/p7267
- 524 Lytra, G., Tempere, S., de Revel, G., & Barbe, J. C. (2012). Impact of perceptive interactions on red
525 wine fruity aroma. *J. Agric. Food Chem., 60*(50), 12260-12269. doi:10.1021/jf302918q
- 526 Ma, Y., Tang, K., Xu, Y., & Li, J.-m. (2017). Characterization of the key aroma compounds in
527 Chinese Vidal icewine by gas chromatography-olfactometry, quantitative measurements,
528 aroma recombination, and omission tests. *Journal of agricultural and food chemistry, 65*(2),
529 394-401. doi:10.1021/acs.jafc.6b04509
- 530 McNamara, A. M., Magidson, P. D., & Linster, C. (2007). Binary mixture perception is affected by
531 concentration of odor components. *Behav. Neurosci., 121*(5), 1132-1136. doi:10.1037/0735-
532 7044.121.5.1132
- 533 Meilgaard, M. C., Carr, B. T., & Civille, G. V. (2006). Selection and training of panel members
534 *Sensory evaluation techniques* (pp. 174-176). New York: CRC Press.
- 535 Miyazawa, T., Gallagher, M., Preti, G., & Wise, P. M. (2009). Odor detection of mixtures of
536 homologous carboxylic acids and coffee aroma compounds by humans. *J. Agric. Food*
537 *Chem., 57*(21), 9895-9901. doi:10.1021/jf901453r
- 538 Moskowitz, H. R., & Barbe, C. D. (1977). Profiling of odor components and their mixtures. *Sensory*
539 *Processes, 1*(3), 212-226.
- 540 Muñoz, A. M. (1986). Development and application of texture reference scales. *J. Sens. Stud., 1*(1),
541 55-83.
- 542 Patte, F., & Laffort, P. (1979). An alternative model of olfactory quantitative interaction in binary

- 543 mixtures. *Chem. Senses*, 4(4), 267-274.
- 544 Prescott, J., Kim, H., & Kim, K.-O. (2008). Cognitive Mediation of Hedonic Changes to Odors
545 Following Exposure. *Chemosens. Percept.*, 1(1), 2-8. doi:10.1007/s12078-007-9004-y
- 546 Rolls, E. T., Kringelbach, M. L., & de Araujo, I. E. T. (2003). Different representations of pleasant
547 and unpleasant odours in the human brain. *Eur. J. Neurosci.*, 18(3), 695-703.
548 doi:10.1046/j.1460-9568.2003.02779.x
- 549 Rouby, C., Pouliot, S., & Bensafi, M. (2009). Odor hedonics and their modulators. *Food. Qual.*
550 *Prefer.*, 20(8), 545-549. doi:10.1016/j.foodqual.2009.05.004
- 551 Seo, H. S., Guarneros, M., Hudson, R., Distel, H., Min, B. C., Kang, J. K., . . . Hummel, T. (2011).
552 Attitudes toward olfaction: a cross-regional study. *Chem. Senses*, 36(2), 177-187.
553 doi:10.1093/chemse/bjq112
- 554 Spence, W., & Guilford, J. P. (1933). The affective value of combinations of odors. *Am. J. Psychol.*,
555 45(3), 495-501.
- 556 Thomas-Danguin, T., & Chastrette, M. (2002). Odour intensity of binary mixtures of odorous
557 compounds. *C. R. Biol.*, 325(7), 767-772. doi:10.1016/s1631-0691(02)01485-3
- 558 Thomas-Danguin, T., Sinding, C., Romagny, S., El Mountassir, F., Atanasova, B., Le Berre, E., . . .
559 Coureaud, G. (2014). The perception of odor objects in everyday life: a review on the
560 processing of odor mixtures. *Front. Psychol.*, 5, 504. doi:10.3389/fpsyg.2014.00504
- 561 Trimmer, C., Keller, A., Murphy, N. R., Snyder, L. L., Willer, J. R., Nagai, M. H., . . . Mainland, J.
562 D. (2019). Genetic variation across the human olfactory receptor repertoire alters odor
563 perception. *Proc. Natl. Acad. Sci. U. S. A.*, 116(19), 9475-9480.
564 doi:10.1073/pnas.1804106115
- 565 Walliczek-Dworschak, U., Poncelet, J., Baum, D., Baki, R., Sinding, C., Warr, J., & Hummel, T.

- 566 (2018). The presentation of olfactory-trigeminal mixed stimuli increases the response to
567 subsequent olfactory stimuli. *J. Agric. Food Chem.*, 66(10), 2312-2318.
568 doi:10.1021/acs.jafc.6b04342
- 569 Weiss, T., Snitz, K., Yablonka, A., Khan, R. M., Gafsou, D., Schneidman, E., & Sobel, N. (2012).
570 Perceptual convergence of multi-component mixtures in olfaction implies an olfactory
571 white. *Proc. Natl. Acad. Sci. U. S. A.*, 109(49), 19959-19964. doi:10.1073/pnas.1208110109
- 572 White, T. L., Thomas-Danguin, T., Olofsson, J. K., Zucco, G. M., & Prescott, J. (2020). Thought for
573 food: Cognitive influences on chemosensory perceptions and preferences. *Food. Qual.*
574 *Prefer.*, 79, 103776. doi:10.1016/j.foodqual.2019.103776
- 575 Wickham, H. (2011). The split-apply-combine strategy for data analysis. *J. Stat. Softw.*, 40(1), 1-29.
- 576 Wise, P. M., Olsson, M. J., & Cain, W. S. (2000). Quantification of odor quality. *Chem. Senses*,
577 25(4), 429-443.
- 578 Zarzo, M. (2008). Psychologic dimensions in the perception of everyday odors: pleasantness and
579 edibility. *J. Sens. Stud.*, 23(3), 354-376. doi:10.1111/j.1745-459X.2008.00160.x

580

Accepted Manuscript

581 **Figures captions**

582 Figure 1 Schematic diagram of psychophysical experiment data collection

583 Figure 2 Intensity and pleasantness of 72 odorants calculated across all the subjects in all the trials

584 Figure 3 Pleasantness of 198 different binary odor mixtures based on 72 different odorants. The top
585 left triangle represents the value of the standard deviation; the bottom right triangle represents the
586 value of the mean pleasantness. The pleasantness values of unmixed odorants are reported on the
587 axes and correspond to the mean value shown in Figure 2. The data from the 24 duplicated trials
588 were not included.

589 Figure 4 τ -value-based model prediction of binary mixtures in the (a) *panel* approach and (b)
590 *individual* approach for the mean condition and the trial condition.

Accepted Manuscript

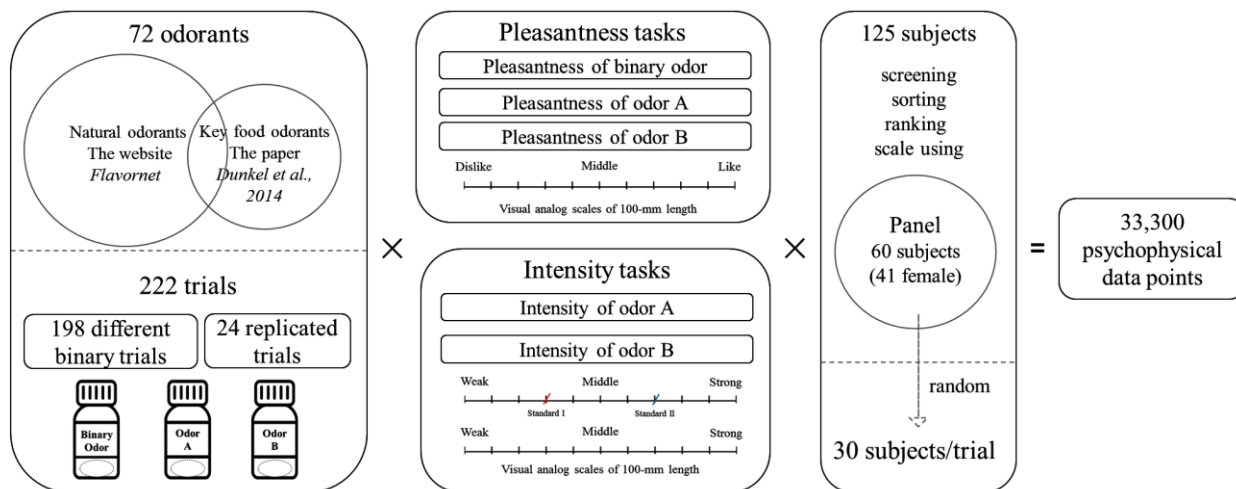
591 Table 1 Prediction Model Performances for Four Trial Groups Calculated with Different
 592 Approaches

Prediction situation	Groups	R^2	RMSE	
<i>Panel approach</i>	<i>Trial condition</i>	Group E	0.868	0.368
		Group I	0.803	0.318
		Group IP	0.862	0.570
		Group P	0.853	0.387
	<i>Mean condition</i>	Group E	0.565	0.606
		Group I	0.704	0.434
		Group IP	0.804	0.666
		Group P	0.636	0.606
<i>Individual approach</i>	<i>Trial condition</i>	Group E	0.461	1.505
		Group I	0.510	1.387
		Group IP	0.548	1.433
		Group P	0.540	1.407
	<i>Mean condition</i>	Group E	0.360	1.601
		Group I	0.433	1.472
		Group IP	0.513	1.495
		Group P	0.478	1.496

593

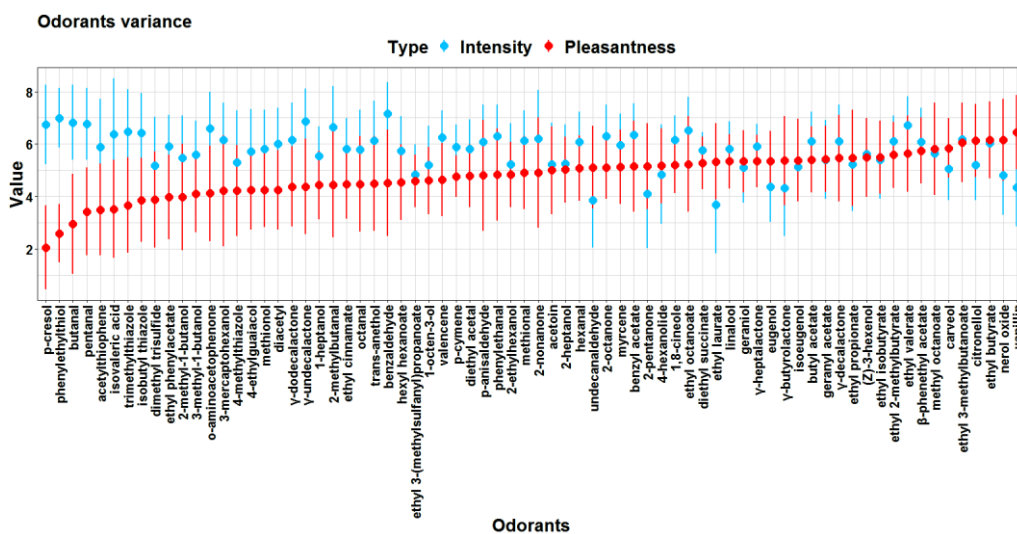
594

Figure 1



Accepted Manuscript

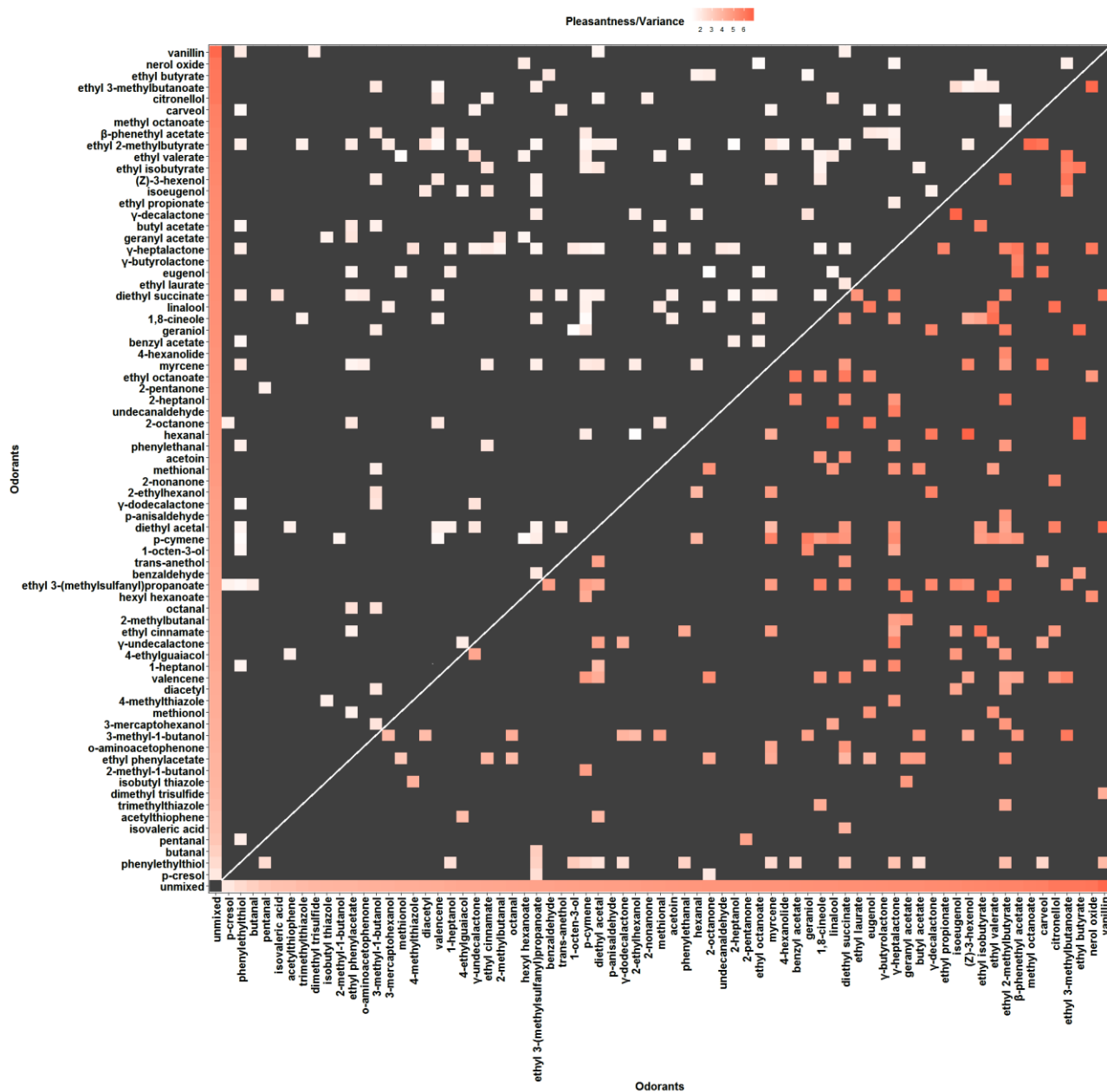
Figure 2



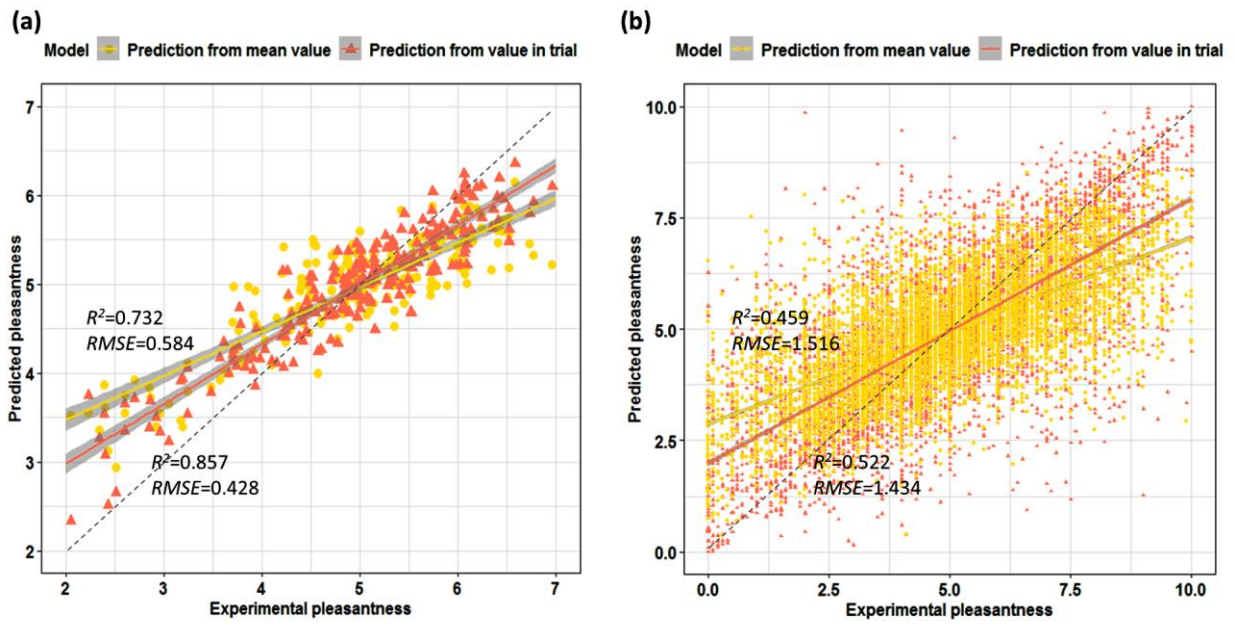
599

600

Figure 3



ACC



Accepted Manuscript