Odor descriptive ratings can predict some odor-color associations in different color features of hue or lightness

Kaori Tamura[1], Tsuyoshi Okamoto[2],

[1] Department of Information and Systems Engineering, Fukuoka Institute of Technology, Fukuoka, Japan

[2] Faculty of Arts and Science, Kyushu University, Fukuoka, Japan

Corresponding Author:

Kaori Tamura[1]

3-30-1, Wajiro-higashi, Higashi-ku, Fukuoka, 811-0295, Japan

Email address: k-tamura@fit.ac.jp

Abstract

Background. Olfactory information can be associated with color information. Researchers have

investigated the role of descriptive ratings of odors on odor-color associations. Research into these

associations should also focus on the differences in odor types. We aimed to identify the odor

descriptive ratings that can predict odor-color corresponding formation, and predict features of the

associated colors from the ratings taking into consideration the differences in the odor types.

Methods. We assessed 13 types of odors and their associated colors in participants with a Japanese

cultural background. The associated colors from odors in the CIE L*a*b* space were subjectively

23   evaluated to prevent the priming effect from selecting color patches. We analyzed the data using

24   Bayesian multilevel modeling, which included the random effects of each odor, for investigating

25   the effect of descriptive ratings on associated colors. We investigated the effects of five descriptive

26   ratings, namely *Edibility*, *Arousal*, *Familiarity*, *Pleasantness*, and *Strength* on the associated

27   colors.

28   **Results.** The Bayesian multilevel model indicated that the odor description of *Edibility* was related

29   to the reddish hues of associated colors in three odors. *Edibility* was related to the yellow hues of

30   colors in the remaining five odors. The *Arousal* description was related to the yellowish hues in

31   two odors. The *Strength* of the tested odors was generally related to the color lightness. The present

32   analysis could contribute in investigating the influence of the olfactory descriptive rating that

33   anticipates the associated color for each odor.

Introduction

36   Olfactory information can provide specific visual information. Some odors are associated

37   with specific colors, such as a lemon-like odor for yellow and a cherry odor for red (Zellner 2013).

38   These odor-color associations have attracted attention and have been extensively investigated

39   (Gilbert et al. 1996; Guerdoux et al. 2014; Kemp & Gilbert 1997). Dematte & colleagues, using

40   an implicit association test, found that some odor-color pairs demonstrated both association (e.g.,

41   strawberry smell and pink) and disassociation (e.g., strawberry smell and turquoise) (Dematte et

42   al. 2006). This report raised the possibility of an implicit association between some odors and

43   colors. Another report indicated that color information can facilitate speeded discrimination of

44   related odors, even when the participants were instructed to ignore the visual information (Dematte

45   et al. 2009). In some cases of odor-color pair, an odor presentation can inhibit visual attention of

46   the associated color. We reported that working memory on orange colors were specifically

47   inhibited under the presentation of decanal, which was a citrus odor included in citrus peels

48   (Tamura et al. 2018). The orange colors represent the olfactory source, citrus peels, and this

49   representation could suggest that the specific decline of orange-color working memory was

50   probably interpreted by odor-color associations. If the mechanism on the association of odor-color

51   pair is revealed, visual attention or olfactory detection would be modulated based on the

52   knowledge of the associated mechanism.

53   Many studies have investigated how some odors were associated with specific colors, but

54   unified interpretation has not been established yet. In the review of crossmodal correspondences

55   (but for visual and auditory correspondences), Spence classed three types of correspondences:

56   structural correspondences resulting from neuronal peculiarities, statistical correspondences based

57   on learning from the environment, and semantically mediated correspondences owing to linguistic

58   terms (Spence 2011). Semantic attributes and learning from experiences have been the main focus

59   in crossmodal studies of vision and olfactory,. For the semantic attributes, the influence on odor-

60   color association of nameability, familiarity (Nehmé et al. 2016; Stevenson et al. 2012) and the

61   edibility (Maric & Jacquot 2013) have been investigated. Some other descriptive ratings, such as

62   food-related factors, intensity ratings, or masculinity/femininity of odors, are associated with

63   corresponding colors (Kemp & Gilbert 1997; Maric & Jacquot 2013; Zellner et al. 2008). These

64   studies support the hypothesis that odor descriptions, such as edibility, intensity, and food-related

65   factors, can mediate odor-color associations. The odor-color associations could be influenced by

66   learning and experiences, such as learning to associate color and taste (Stevenson et al. 2000).

67   Moreover, the cultural backgrounds (Jacquot et al. 2016; Levitan et al. 2014; Nehmé et al. 2016)

68   influence the odor-color association. Considered together, the odor-color association could be

69   affected by semantic consistency, learning experience, and cultural contexts.

70   Other reports suggested the effect of linguistic system. Western language speakers tend

71   to represent smells as labeling of the olfactory source; however, individuals have abstract

72   terminology for odors in Southeast Asia (Majid & Burenhult 2014). de Valk et al compared Maniq

73   (Southeast Asian minorities) individuals with abstract smell terms and Western language speakers

74   (Thai and Dutch participants) (de Valk et al. 2017). They suggested that when individuals have

75   different language systems for olfaction, their strategy to choose associated colors with smell

76   would be different. Therefore, individuals with similar cultural backgrounds and linguistic systems

77   possibly share several common odor-color associations.

78   Although we can assume that some olfactory descriptive evaluations would relate to

79   associated colors among individuals with common culture, predicting the association and color

80   characteristics based on the descriptive ratings is challenging. If we are able to determine the

81   influence of olfactory description on the features of associated colors, it would contribute in

82   revealing the mechanism of the odor-color association formation. Our main questions are: 1) which

83   olfactory description can be useful to expect associated colors, and 2) how descriptive ratings of

84   odors will influence the hue and lightness of the associated colors. To solve these problems, a new

85   prediction method should be developed to predict the contribution of odor descriptive ratings for

86   the association of specific colors.

87   This study aimed to investigate the olfactory descriptive ratings that would be useful in

88 expecting an association color for each odor, and predicting the influence of the ratings on hue and

89 lightness of the associated colors. Even when the individuals shared common background culture,

90 the relationship between the olfactory descriptive ratings and color association could vary across

91 the odor types. Herein, our model aimed to determine the influence of olfactory description

92 accounting for the differences in the odor types, and not to determine the general feature among

93 all the odors to predict the associated colors.

94   We assessed 13 types of odors, their associated colors, and their descriptive evaluations

95 using the aforementioned methods. The tested odors were rated using five descriptive ratings as

96 follows: *Edibility*, *Arousal*, *Familiarity*, *Pleasantness*, and *Strength.* To predict the effect of the

97 descriptive attributes, we introduced a Bayesian multilevel regression model with the data of

98 associated colors for the assessed odors to avoid type-1 error due to unnecessary multiple

99 comparisons (Gelman et al. 2012).

100

Materials and Methods

102   The ethics committee of Kyushu University approved the current experiment. All

103 procedures were performed in accordance with the approved guidelines of the ethics committee of

104 the Faculty of Arts and Science, Kyushu University (#201907). All participants provided written

105 informed consent in accordance with the tenets of the Declaration of Helsinki before participation.

Participants

106

107   We recruited 23 university students for this study (women, n = 11; men, n = 12; and mean

108   age ± SD = 20 ± 1.6 years). None of the participants displayed color vision deficiencies following

109   the Ishihara's test. Based on self-reports, none of the participants had olfactory or neurological

110   deficits. As the odor-color association depends on cultural and language backgrounds (Levitan et

111   al. 2014; Majid & Burenhult 2014; Majid et al. 2018), we ensured that all participants were native

112   Japanese speakers and from Japanese cultural backgrounds. The participants were instructed to

113   stop eating and drinking 1 hour before the experiment; however, they were permitted to drink

114   water.

Environment and display settings

115

116   All visual stimuli were presented on a laptop computer screen (MacBook Pro 13-inch,

117   Retina display, resolution 2560 × 1600) using Psychtoolbox-3 (Brainard 1997; Kleiner et al. 2007)

118   programmed in MATLAB (MathWorks, Inc., Natick, MA, USA). The monitor was calibrated

119   following standard methods (Brainard et al. 2002) using a Chroma Meter (CS150, KONICA

120   MINOLTA. INC. Tokyo, Japan). We placed the laptop computer display on a portable

121   photography box measuring 60 × 60 cm to control the lightness of the environment (Fig. 1a). The

122   backdrop was black and there was no light-emitting diode inside the box during the experiments.

Odor stimuli

123

124   We assessed 13 odors in this study (Table 1). According to a previous report, they were

125   diluted to control the odor intensity, which was almost equivalent (Bushdid et al. 2014).

126   Five microliters of the odorant solution prepared according to Table 1 was added dropwise to 0.5

127   × 0.5 cm of cotton wool. Three cotton wool samples with odorant drops were encapsulated in a 20

128   mL vial (Fig. 1b), and the solution was volatilized for at least 30 min. Immediately before the

129   participant sniffed the sample, the cotton wool was removed and only the odor gas was presented.

130   We counterbalanced the order of presentation of the odorants among the participants. The same

131   13 odorants were used in both the experiments; the order of presentation was different within the

132   two experiments. We also changed the order of presenting the odorants among the participants. In

133   addition, the participants were not notified that "the odor substances used in the first and second

134   experiments were identical." The substance name was not written on the vial, and the odor was

135   presented with care such that the participants could not predict the type of odor presented.

Experiment

136

137   The participants were instructed to sniff 13 different odorants and indicate the color and

138   semantics associated with each odor. The odor was enclosed in a bottle; the participants opened

139   the bottle upon instruction and sniffed it. Immediately after completing the associative

140   color/semantics evaluation response, the participants sniffed coffee beans for 10 s. Following a 2-

141 min break, they smelled the subsequent odorant. The room was ventilated during the break. All

142 participants completed the task twice on different days.

143   We requested the participants to respond to an associated color with a presented odor and

144 to rate several descriptions. The procedure and color settings were determined in a previous study

145 (Tamura et al. 2018). Each participant was handed a vial containing the gaseous odor and asked to

146 sniff the odor. Consequently, the color associated with the odor was reported. First, the participants

147 were asked concerning the hue angle of the associated color and they rotated a cursor

148 corresponding to the hue angle. The angle between the cursor and the center of the circle

149 determined the hue value of the square. The square was presented at the center of the display, and

150 the color was subsequently changed following the cursor movement (Tamura et al. 2018). The

151 colors were determined within a circle in the CIELa*b* color space, with a center space at L = 70,

152 a* = 20, b* = 38, and a radius of 60 (Zhang & Luck 2008) (Fig. 1d). They clicked upon deciding

153 that the current color hue was most associated with the presented odor. Subsequently, we presented

154 three colors with different lightness values of the selected color (L = 40, 70, and 100). The

155 participants selected the lightness of the color that was most associated with the odor (Fig. 1c).

156   After deciding the associated color, they were instructed to complete the responses to five

157 descriptor items as follows: *Strength*, *Pleasantness*, *Familiarity*, *Edibility*, and *Arousal*, using the

158 visual analog scale (VAS) ranging from 0 (completely different) to 1 (very applicable). For

159   example in Strength evaluation, 1 indicates very strong, 0 indicates very weak, and 0.5 indicates

160   moderate strength. *Strength* and *Edibility* would relate to primitive odor evaluation. *Pleasantness*

161   and *Familiarity* would reflect basic subjective evaluation for odors, and *Arousal* would relate to

162   physiological states. The relationship of color-odor association with descriptor items of *Strength*

163   and *Edibility* have been reported previously (Kemp & Gilbert 1997; Maric & Jacquot 2013). To

164   investigate the influence by different descriptor items, *Pleasantness*, *Familiarity*, and *Arousal*

165   were added. *Pleasantness* and *Familiarity* have been used in related olfactory studies with

166   subjective ratings (e.g., (Delplanque et al. 2015; Ferdenzi et al. 2017; Ferdenzi et al. 2013;

167   Huisman & Majid 2018)). These terms were also used for color-odor association studies (Nehmé

168   et al. 2016). *Arousal* ratings can be informative to show the participants' affective states, which

169   has been reported previously *Arousal* ratings to odors reportedly correlated with the autonomic

170   system (Bensafi et al. 2002).

171   Our method attempted to measure the colors associated with odors to prevent visual

172   priming effect while choosing associate colors. Conventional studies assessed the selection based

173   on several color patches after sniffing the odors (de Valk et al. 2017; Gilbert et al. 1996; Levitan

174   et al. 2014; Majid & Burenhult 2014; Majid et al. 2018). We were concerned that the color patch

175   presentations may could result in the priming of responses since visual priming can support

176   olfactory identification and odor-naming (Gottfried & Dolan 2003; Guerdoux et al. 2014; Morrot

177   et al. 2001; Olofsson & Gottfried 2015; Robinson et al. 2015; van Beilen et al. 2011).

178   **Bayesian Estimation**

179   For the statistical analysis, we performed Bayesian estimation with several models. The

180   models were fitted using the R environment (ver.3.4.0) and RStan (ver.2.2.1) with the Markov

181   chain Monte Carlo (MCMC) method. All estimates were made with 3,000 samplings, running four

182   chains to generate random numbers, and a burn-in period of 1,000. We used the Gelman-Rubin

183   statistics $\hat{R}$ to determine if the MCMC estimation converged for all estimation parameters. $\hat{R}$ is

184   generally considered to converge as it approaches 1.10, and each model fit produces $\hat{R}$ <1.10.

185

186   **Bayesian Multilevel Regression analysis**

187   We used Bayesian multilevel regression models to estimate the effects of the following

188   five descriptor items on color responses: *Strength*, *Pleasantness*, *Familiarity*, *Edibility*, and

189   *Arousal*. The multilevel models estimated the L*-, a*-, and b*- axis values using odor-level effects.

190   The values of the L*-, a*-, and b*- axes were divided by 100 for normalization. The Bayesian

191   multilevel regression did not require concern about type-1 error from multiple comparisons

192   because the model did not assume a null hypothesis (Gelman et al. 2012).

193   We modeled the response value of the a*-axis for the associated colors by each odor as a

194   normal distribution as follows:

195

$$a_{[j]}^* \sim Normal(\alpha_{0[i]} + \alpha_{S[i]}Strength_{[i]} + \alpha_{P[i]}Pleasantness_{[i]} + \alpha_{F[i]}Familiarity_{[i]} + \alpha_{E[i]}$$
$$Edibility_{[i]} + \alpha_{A[i]}Arousal_{[i]}, \sigma_{a[i]})$$

196

197
$$\sigma_{a[i]} > 0$$

198

199   where i indicates the odor ID and j denotes the data index. The intercept ($\alpha_{0[i]}$) and each

200   coefficient, $\alpha_{X[i]}$, followed a normal distribution with mean coefficients as follows:

201

202
$$\alpha_{0[i]} \sim Normal(\alpha_{0\_all}, \sigma_{\alpha0})$$

203
$$\alpha_{S[i]} \sim Normal(\alpha_{S\_all}, \sigma_{\alpha S})$$

204
$$\alpha_{P[i]} \sim Normal(\alpha_{P\_all}, \sigma_{\alpha P})$$

205
$$\alpha_{F[i]} \sim Normal(\alpha_{F\_all}, \sigma_{\alpha F})$$

206
$$\alpha_{E[i]} \sim Normal(\alpha_{E\_all}, \sigma_{\alpha E})$$

207
$$\alpha_{A[i]} \sim Normal(\alpha_{A\_all}, \sigma_{\alpha A})$$

208

209   where α_{n_all} indicates the average coefficient across all odorants. The prior distributions

210   for the parameters of the standard deviations were as follows:

211

212
$$\sigma_{\alpha0} \sim Normal(0, 5) \ (\sigma_{\alpha0} > 0)$$

213 $$\sigma_{\alpha S} \sim Normal(0, 5)\ (\sigma_{\alpha S} > 0).$$

214 $$\sigma_{\alpha P} \sim Normal(0, 5)\ (\sigma_{\alpha P} > 0).$$

215 $$\sigma_{\alpha F} \sim Normal(0, 5)\ (\sigma_{\alpha F} > 0).$$

216 $$\sigma_{\alpha E} \sim Normal(0, 5)\ (\sigma_{\alpha E} > 0).$$

217 $$\sigma_{\alpha A} \sim Normal(0, 5)\ (\sigma_{\alpha A} > 0).$$

218

219

220 Regarding the model for a* value estimation, we modeled the b*-axis values as follows:

221

222 $$b_{[j]}^{*} \sim Normal(\beta_{0[i]} + \beta_{S[i]}Strength_{[i]} + \beta_{P[i]}Pleasantness_{[i]} + \beta_{F[i]}Familiarity_{[i]} + \beta_{E[i]}Edibility_{[i]} + \beta_{A[i]}Arousal_{[i]}, \sigma_{b[i]})$$

223

224 where each coefficient followed normal distribution with mean coefficients as follows:

225

226 $$\beta_{0[i]} \sim Normal(\beta_{0\_all}, \sigma_{\beta 0})$$

227 $$\beta_{S[i]} \sim Normal(\beta_{S\_all}, \sigma_{\beta S})$$

228 $$\beta_{P[i]} \sim Normal(\beta_{P\_all}, \sigma_{\beta P})$$

229 $$\beta_{F[i]} \sim Normal(\beta_{F\_all}, \sigma_{\beta F})$$

230 $$\beta_{E[i]} \sim Normal(\beta_{E\_all}, \sigma_{\beta E})$$

231 $$\beta_{A[i]} \sim Normal(\alpha_{A\_all}, \sigma_{\beta A})$$

232

233   where β_{b_alln} indicates the average coefficient across all odorants. The prior distributions

234   for the parameters of standard deviations in our model were as follows:

235 $$\sigma_{\beta bn} \sim Normal(0, 5)$$

236   where $\sigma_{\beta bn} > 0$.

237

238   Similar to the steps with a* and b* values, we model the L-axis values as follows:

239 $$L_{[j]}^{*} \sim Normal(\lambda_{0[i]} + \lambda_{S[i]}Strength_{[i]} + \lambda_{P[i]}Pleasantness_{[i]} + \lambda_{F[i]}Familiarity_{[i]} + \lambda_{E[i]}Edibility_{[i]} + \lambda_{A[i]}Arousal_{[i]}, \sigma_{L[i]})$$

240

241   and the prior distributions for parameters were as follows:

242 $$\lambda_{0[i]} \sim Normal(\lambda_{0\_all}, \sigma_{\lambda 0})$$

243 $$\lambda_{S[i]} \sim Normal(\lambda_{S\_all}, \sigma_{\lambda S})$$

244 $$\lambda_{P[i]} \sim Normal(\lambda_{P\_all}, \sigma_{\lambda P})$$

245 $$\lambda_{F[i]} \sim Normal(\beta_{F\_all}, \sigma_{\lambda F})$$

246 $$\lambda_{E[i]} \sim Normal(\beta_{E\_all}, \sigma_{\lambda E})$$

247 $$\lambda_{A[i]} \sim Normal(\alpha_{A\_all}, \sigma_{\lambda A})$$

248 $$\sigma_{\lambda n} \sim Normal(0, 5)$$

249

250   with $\lambda_{X[i]}$ indicating the average coefficient across all odorants, and $\sigma_{\lambda n}$ >0.

251

Bayesian Within-Subject Analysis for Color Response Reproducibility

253   The participants repeated the associated color response twice on different days. We

254   performed Bayesian analysis to estimate the mean difference in color responses between days to

255   demonstrate the reproducibility of the color responses among the participants.

256   We modeled the difference in a*-axis values measured from the associated color

257   responses as a normal distribution as follows:

$$\Delta a^{*}_{[i,j]} \sim Normal(\mu_{odor\_a[i]}, \sigma_{odor\_a[i]})$$

$$\mu_{odor\_a[i]} \sim Normal(\mu_{all\_a}, \sigma_{all\_a})$$

$$\sigma_{odor\_a[i]} > 0$$

$$\sigma_{all\_a} > 0$$

262

263   where i indicates the odor ID, j denotes the data index, and $\Delta a^{*}_{[i,j]}$ indicates the difference

264   between the a*-value on day 2 and day 1 for each participant and each odorant. $\mu_{odor\_a[i]}$ indicates

265   the mean difference of $\Delta a^{*}_{[i,j]}$ within an odor and $\sigma_{odor\_a[i]}$ indicates its standard deviation.

266    $\mu_{odor\_a[i]}$ followed a normal distribution with a mean difference across the odors, μ_{all_a}, and a

267   standard deviation, σ_{all_a}. Moreover, we modeled the difference in the b*- and L-axis values

268   between days as $\Delta a^{*}_{[i,j]}$.

Results

Days-differences of Associated Colors within Participants

271   Perception from olfaction could vary among participants. We analyzed whether the

272   responses derived from the odorants were consisted among participants. The conventional

273   common approach cannot support the hypothesis that "the mean of differences was equally 0." To

274   confirm within-participant consistency with the responses derived from the odorants, we estimated

275   the posterior distribution and its 95% Bayesian confidence interval (CI) of the mean day

276   differences within the participants. For the a*-, b*-, and L*-axis values, there were no parameters

277   of day difference whose 95% CI did not include 0 (Fig. 2). The associated color responses did not

278   significantly fluctuate with the days in response to the odorant. The results indicated that the

279   associated color responses did not significantly fluctuate with the days in response to any odorant.

280

Confirmation of the Multicollinearity for Multilevel Regression

282   Before implementing the multilevel regression, we confirmed the multicollinearity of five

283   descriptive ratings. Subsequently, we performed Pearson correlation analysis to demonstrate the

284   correlation coefficients and any absolute values of the coefficients ≤0.70 (Table 2), which is the

285   lower limit of a strong correlation in psychology (Akoglu 2018). We included all descriptive rating

286   data in the multilevel regression model according to the results.

287   **Bayesian multilevel regression**

288   First, we confirmed the model for a*-value estimation and the distribution of the

289   coefficient parameters with odor descriptors. A significantly positive estimated parameter with

290   ratings of a semantic descriptor indicated that a higher descriptor rating would allow the associated

291   colors to be reddish. By contrast, a significantly negative estimated parameter suggested that a

292   higher descriptor would allow the associated colors to be greenish.

293   The multilevel model for a*-values estimated the parameters with odorant-level effects.

294   We used a multilevel Bayesian regression model that included random intercepts and slopes for

295   each odor to estimate the effect of each descriptive rating on the associated colors. We estimated

296   the coefficients of the five descriptive ratings, and their 95% CIs are demonstrated for each odorant

297   (Fig. 3). For the 95% CIs of *Edibility*, the three odors, including 2-ethyl pyrazine, limonene, and

298   strawberry aldehyde, did not significantly overlap with zero (Fig. 3). The results indicated colors

299   associated with the three odors related to *Edibility* ratings. An increase in the *Edibility* ratings of

300   these odorants would make the associated colors more reddish. The remaining odors did not

301   display a practical difference in the coefficients of *Edibility* from zero in the a*-value predictive

302   model. The remaining descriptive ratings did not demonstrate any practical differences from zero

303   for any odor.

304   Fig. 4 depicts the colors associated with the three odors that showed higher coefficients

305   with *Edibility* ratings. The color responses were reddish, according to the increase in *Edibility*

306   ratings for the three odorants (Fig. 4). The original colors indicated the native responses of the

307   participants. To demonstrate the relationship between the a*-axis values and *Edibility* ratings, we

308   fixed the b*- and L*- parameters with the initial settings. Subsequently, we changed the a*-values

309   only according to the responses of the associated colors (Fig. 4, middle row). The right row denotes

310   changes in the a*-value (Fig. 4). The associated colors were greenish and reddish for low and high

311   *Edibility* ratings in the three odors, respectively. These a*-value changes corresponded to the

312   *Edibility* ratings.

313   Consequently, we confirmed the model that estimated the b*values and the distribution

314   of estimates of the coefficient parameters with their odor descriptors. A significantly positive

315   estimated parameter with ratings of a semantic descriptor indicated that a higher descriptor rating

316   would allow the associated colors to be yellowish, whereas a lower rating would allow the colors

317   to be bluish. An estimated parameter that was significantly negative from 0 suggested that a higher

318   descriptor would allow the associated colors to be bluish along the yellow-blue axis.

319   For the *Edibility* ratings, five odorants, including hydroxy citronellal, butyl acetate, (1S)-

320   (-)-alpha-pinene, trimethyl amine (30%), and 2,3-Dimethylpyrazine, displayed significant

321 coefficients. The 95% CI of the five odors did not significantly overlap with zero (Fig. 5). In the

322 results of the a*-prediction model, the five odors did not reveal significant coefficients with

323 *Edibility* (Fig. 3). Fig. 6 represents the color responses from the participants with *Edibility* ratings.

324 To demonstrate the relationship between the b*-axis values and *Edibility* ratings, we fixed the a*-

325 and L*- parameters with the initial settings. Moreover, we changed the b*values only according

326 to the responses of the associated colors (Fig. 6, middle row). The associated colors were bluish

327 for low *Edibility* ratings.

328 For *Arousal* ratings, the two odorants, namely hydroxy citronellal and 4-methyl-3-penten-

329 2-one, displayed higher coefficients (Fig. 7). The associated colors would be more bluish for these

330 odorants following low *Arousal* ratings. The remaining descriptive ratings did not reveal any

331 practical differences from zero for any odor.

332 The model for L*-value prediction demonstrated significant coefficients for *Strength* and

333 intercepts for all odorants. The coefficients of *Strength* ratings indicated that the associated colors

334 would be darker for all odorants following an increase in ratings (Fig. 8). We displayed some

335 examples to exhibit the relationship between the *Strength* ratings and the lightness of colors (Fig.

336 9), which revealed that the colors would be darker for higher ratings.

337

Discussion

338

339   There were two purposes of this study. The first aim was to identify the descriptive

340   evaluations of odors to predict the associated colors, while the second aim was to predict the

341   influence of the ratings on hue and lightness of the associated colors, accounting for the differences

342   in the odor types. The results demonstrated that the *Edibility* and *Arousal* ratings were related to

343   the color hues with several odors, represented by the a*- and b*- axes. Based on the odor type, the

344   effects of *Edibility* on color hue are represented in different hue axes, namely a* or b*. The

345   *Strength* of the odor was related to the color lightness in any odorant. The descriptive ratings of

346   *Edibility* and *Arousal* mediated the hues of associated colors for specific odors, and odor *Strength*

347   generally mediated the lightness of the associated colors.

348   First, we will discuss the effects of *Edibility* on odor-color associations. The multilevel

349   regression model using Bayesian estimation revealed that *Edibility* and *Arousal* ratings were

350   related to some odor-color associations in the color hue. The positive values in the *Edibility*

351   coefficients are presented in three odors for the a*- regression model. The associated colors of

352   these three odors were reddish for higher *Edibility* ratings. The *Edibility* coefficients for b*-

353   regression demonstrated significant positive coefficients for the five odorants. The positive

354   coefficients in the b*- model indicated that the associated colors of the five odorants were

355   yellowish following an increase in *Edibility*. The specificity of the *Edibility* coefficients with the

356 two color-hue regression models, i.e., a*- and b*- models in CIE L*a*b* space, resulted in the

357 following two suggestions: 1) the descriptor of *Edibility* can mediate the associated colors with

358 various odorants (in this case, eight of 13 odorants) and 2) the color-associations were mediated

359 by the *Edibility* ratings in either of two axes, namely a*- or b*- in the CIEL*a*b* color space. The

360 associated colors are not simultaneously mediated by the a*- and b*- values. These speculations

361 were consistent with a report that demonstrated that the odors with higher edibility tended to be

362 yellow colors (Maric & Jacquot 2013). On the other hand, for strawberry odors, several studies

363 reported conflicting associated colors, red or pink (Dematte et al. 2006; Osterbauer et al. 2005);

364 however, green was reported in an Australian study (Stevenson et al. 2012). In our analysis,

365 strawberry aldehyde was associated with reddish colors when the odor was evaluated highly

366 edible. Moreover, the odor from almond essence was reportedly associated with blue color

367 (Stevenson et al. 2012); however, our model in 2-ethyl pyrazine, which is the main component of

368 burned nuts, demonstrated reddish colors when highly edible. The varied association could be

369 influenced by the difference in the regions and cultural backgrounds (Jacquot et al. 2016; Levitan

370 et al. 2014; Nehmé et al. 2016) between Western and Japanese people in East Asia. Cultural

371 backgrounds can vary in the olfactory perception, recognition performance (Chrea et al. 2004),

372 and pleasantness of odors (Herz 2005).

373   Our results on the effects of *Edibility* on odor-color associations were supported by

374   conventional studies, which have proposed the importance of edibility in odor description and

375   olfactory discrimination in terms of psychological and neurophysiological aspects. For example,

376   in the odor naming task of Dutch words, odors that were evaluated as "edible" were correctly

377   labeled more frequently than those that were considered of "low edibility" (Huisman & Majid

378   2018). In the neuronal activity in the olfactory system, edibility (or toxicity as the flip side of

379   edibility) is one of the primary dimensions of human odor perception (Haddad et al. 2010). Smeets

380   and Dijksterhuis have reported on the efficacy of food odors as goal primes, such as digestion and

381   appetite regulation (Smeets & Dijksterhuis 2014). Gustatory sensation can be affected other

382   sensory inputs. Oleszkiewicz and colleagues reported that individuals with blindness and deafness

383   showed different taste sensitivity and liking, probably owing to less gustatory experiences

384   (Oleszkiewicz et al. 2023). Functional MRI studies have demonstrated that the presentation of

385   congruent odor-color pairs induces higher activity in the orbitofrontal cortex, whose activity

386   diminishes by satiety, than incongruent odor-color combinations (Osterbauer et al. 2005). Our

387   finding that the odor-color association was mediated by the *Edibility* rating was consistent with

388   these studies.

389   Regarding the b*-values in the blue and yellow axes in the CIE L*a*b* space, *Arousal*

390   ratings displayed higher coefficients for two odorants, namely hydroxy citronellal and 4-Methyl-

391   3-penten-2-one. These odors may have simultaneously activated trigeminal sensations with

392   olfactory sensations owing to the olfactory features of these odorants. According to the TGSC

393   Information System, the odor types of hydroxy citronellal were "fresh," and those of 4-Methyl-3-

394   penten-2-one were "pungent." One probable interpretation is that these odorants activate the

395   intranasal chemosensory trigeminal system. The trigeminal sensation induces arousal feelings, and

396   the *Arousal* rating may affect the b*-values. These results suggested that trigeminal sensation

397   induced a yellowish color. Michael et al. reported that some colors can relate to specific nasal

398   thermal sensations (Michael & Rolhion 2008). However, we could not determine a relationship

399   between the color association and nasal sensation in the present study. This necessitates further

400   investigation to determine the association between yellowish color and arousal.

401   Although several odors showed significant relationships with a*- or b*- values in the

402   models as discussed above, the remaining odors did not demonstrate any significant relationship

403   between the associated color hues and present descriptors. Our findings could not conclude that

404   the descriptive ratings of odors did not mediate the pairs of odor-color associations. The present

405   experiment investigated only five descriptors of odor impressions. Researchers should assess other

406   candidates for descriptive ratings to determine if these ratings relate to the parameters of the

407   associated colors.

408   In the L*-axis of lightness, the *Strength* rating was negative from 0 for all the tested

409   odorants. Thus, the associated colors of the tested odorant were darker upon evaluating the

410   odorants as strong. This finding was consistent with those of a previous study that reported on an

411   inverse relationship between odor intensity and color lightness (Kemp & Gilbert 1997). We

412   confirmed that odor intensity can globally modulate the lightness of the associated color using our

413   procedure and analyses.

414   This study introduced a Bayesian multilevel regression model to predict the effects of

415   descriptive ratings on the parameters of the associated colors. This multilevel model enabled the

416   incorporation of odor-specific effects that varied across odor types. Furthermore, such models can

417   represent complex structures by assuming conditional dependencies. The Bayesian multilevel

418   model did not begin with the assumption that the null hypothesis was true; therefore, this method

419   did not consider type-1 error from multiple comparisons, as do conventional statistical methods

420   (Gelman et al. 2012). The present multilevel model included random slopes and intercepts among

421   the odors, without multiple comparisons. Using the aforementioned model, we estimated each odor

422   parameter derived from the common parameters of all odors. This estimation could represent the

423   difference in odors with descriptive ratings using the identical model.

424   Our measurement method had several limitations. Our experiment determined the response colors

425   within a circle in the CIE L*a*b* with a fixed radius. It aimed to prevent manipulative confusion

426   and errors during the response to the associated colors. For further investigation, researchers

427   should measure the associated colors using free radius of color hues and a continuous degree of

428   lightness. Furthermore, the measurement of descriptive ratings requires improvement. The study

429   warranted higher linguistic descriptors to elucidate the relationship between descriptive expression

430   and odor-color association; nonetheless, our findings confirmed that the *Edibility* rating of

431   odorants could mediate odor-color associations. Future studies should focus on variable food-

432   related descriptors and odor-color associations with continuous measurements.

433   We do not enforce that the tested odor should be associated with the colors as

434   demonstrated in our manuscript (e.g., 2-ethyl pyrazine and reddish colors). Our models aimed to

435   investigate the influence of olfactory descriptive ratings on the feature of associated colors.

436   Furthermore, investigation was only performed in individuals with a similar cultural background

437   in Japan. Cross cultural difference comparison would be possible if the proposed method is used

438   for other populations with different cultural backgrounds.

439   ## Conclusions

440   In summary, we investigated the impact of descriptive ratings on the associated colors

441   from odors using the Bayesian multilevel regression model. Our analysis could predict the

442   olfactory description that would be useful to expect an associated color for each odor. The results

443   indicated that their *Edibility* or *Arousal* ratings mediated the hue values of the associated colors of

444   some odors. In contrast, the *Strength* of odors generally mediated the lightness of their associated

445   colors. Our investigation and measurement procedures will contribute to the understanding of

446   odor-color association.

447

448 **Declarations**

449 **Ethics approval:** The ethics committee of Kyushu University approved the current experiment.

450 All procedures were performed in accordance with the approved guidelines of the ethics committee

451 of the Faculty of Arts and Science, Kyushu University.

452 **Consent to participate:** All participants provided written informed consent in accordance with

453 the tenets of the Declaration of Helsinki before participation.

454 **Consent to publish**:

455 The authors affirm that human research participants provided informed consent for publication of

456 the recorded data.

457

References

458

459 Akoglu H. 2018. User's guide to correlation coefficients. *Turk J Emerg Med* 18:91-93. 10.1016/j.tjem.2018.08.001

460 Bensafi M, Rouby C, Farget V, Bertrand B, Vigouroux M, and Holley A. 2002. Autonomic nervous system responses
461   to odours: the role of pleasantness and arousal. *Chemical Senses* 27:703-709. 10.1093/chemse/27.8.703

462 Brainard DH. 1997. The Psychophysics Toolbox. *Spatial Vision* 10:433-436. 10.1163/156856897X00357

463 Brainard DH, Pelli DG, and Robson T. 2002. Display Characterization. *Encyclopedia of Imaging Science and*
464   *Technology*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 267-272.

465 Bushdid C, Magnasco MO, Vosshall LB, and Keller A. 2014. Humans can discriminate more than 1 trillion olfactory
466   stimuli. *Science* 343:1370-1372. 10.1126/science.1249168

467 Chrea C, Valentin D, Sulmont-Rossé C, Ly Mai H, Hoang Nguyen D, and Abdi H. 2004. Culture and odor
468   categorization: agreement between cultures depends upon the odors. *Food Quality and Preference* 15:669-
469   679. 10.1016/j.foodqual.2003.10.005

470 de Valk JM, Wnuk E, Huisman JLA, and Majid A. 2017. Odor-color associations differ with verbal descriptors for
471   odors: A comparison of three linguistically diverse groups. *Psychon Bull Rev* 24:1171-1179.
472   10.3758/s13423-016-1179-2

473 Delplanque S, Coppin G, Bloesch L, Cayeux I, and Sander D. 2015. The mere exposure effect depends on an odor's
474   initial pleasantness. *Front Psychol* 6:911. 10.3389/fpsyg.2015.00920

475 Dematte ML, Sanabria D, and Spence C. 2006. Cross-modal associations between odors and colors. *Chem Senses*
476   31:531-538. 10.1093/chemse/bjj057

477 Dematte ML, Sanabria D, and Spence C. 2009. Olfactory discrimination: when vision matters? *Chem Senses* 34:103-
478   109. 10.1093/chemse/bjn055

479 Ferdenzi C, Joussain P, Digard B, Luneau L, Djordjevic J, and Bensafi M. 2017. Individual Differences in Verbal and
480   Non-Verbal Affective Responses to Smells: Influence of Odor Label Across Cultures. *Chem Senses* 42:37-
481   46. 10.1093/chemse/bjw098

482 Ferdenzi C, Roberts SC, Schirmer A, Delplanque S, Cekic S, Porcherot C, Cayeux I, Sander D, and Grandjean D.
483   2013. Variability of affective responses to odors: culture, gender, and olfactory knowledge. *Chem Senses*
484   38:175-186. 10.1093/chemse/bjs083

485 Gelman A, Hill J, and Yajima M. 2012. Why We (Usually) Don't Have to Worry About Multiple Comparisons.
486   *Journal of Research on Educational Effectiveness* 5:189-211. 10.1080/19345747.2011.618213

487 Gilbert AN, Martin R, and Kemp SE. 1996. Cross-modal correspondence between vision and olfaction: the color of
488   smells. *American Journal of Psychology* 109:335-351. 10.2307/1423010

489 Gottfried JA, and Dolan RJ. 2003. The nose smells what the eye sees: crossmodal visual facilitation of human olfactory
490   perception. *Neuron* 39:375-386. 10.1016/s0896-6273(03)00392-1

491 Guerdoux E, Trouillet R, and Brouillet D. 2014. Olfactory-visual congruence effects stable across ages: yellow is
492   warmer when it is pleasantly lemony. *Atten Percept Psychophys* 76:1280-1286. 10.3758/s13414-014-0703-

493   6

494   Haddad R, Weiss T, Khan R, Nadler B, Mandairon N, Bensafi M, Schneidman E, and Sobel N. 2010. Global features

495   of neural activity in the olfactory system form a parallel code that predicts olfactory behavior and perception.

496   *J Neurosci* 30:9017-9026. 10.1523/JNEUROSCI.0398-10.2010

497   Herz RS. 2005. Odor-associative learning and emotion: effects on perception and behavior. *Chem Senses* 30 Suppl

498   1:i250-251. 10.1093/chemse/bjh209

499   Huisman JLA, and Majid A. 2018. Psycholinguistic variables matter in odor naming. *Mem Cognit* 46:577-588.

500   10.3758/s13421-017-0785-1

501   Jacquot M, Noel F, Velasco C, and Spence C. 2016. On the Colours of Odours. *Chemosensory Perception* 9:79-93.

502   10.1007/s12078-016-9209-z

503   Kemp SE, and Gilbert AN. 1997. Odor intensity and color lightness are correlated sensory dimensions. *American*

504   *Journal of Psychology* 110:35-46. 10.2307/1423699

505   Kleiner M, Brainard D, Pelli D, Ingling A, Murray R, and Broussard C. 2007. What's new in psychtoolbox-3.

506   *Perception* 36:1-16.

507   Levitan CA, Ren J, Woods AT, Boesveldt S, Chan JS, McKenzie KJ, Dodson M, Levin JA, Leong CX, and van den

508   Bosch JJ. 2014. Cross-cultural color-odor associations. *PloS One* 9:e101651. 10.1371/journal.pone.0101651

509   Majid A, and Burenhult N. 2014. Odors are expressible in language, as long as you speak the right language. *Cognition*

510   130:266-270. 10.1016/j.cognition.2013.11.004

511   Majid A, Burenhult N, Stensmyr M, de Valk J, and Hansson BS. 2018. Olfactory language and abstraction across

512   cultures. *Philos Trans R Soc Lond B Biol Sci* 373:20170139. 10.1098/rstb.2017.0139

513   Maric Y, and Jacquot M. 2013. Contribution to understanding odour–colour associations. *Food Quality and*

514   *Preference* 27:191-195. 10.1016/j.foodqual.2012.05.001

515   Michael GA, and Rolhion P. 2008. Cool colors: color-induced nasal thermal sensations. *Neurosci Lett* 436:141-144.

516   10.1016/j.neulet.2008.03.007

517   Morrot G, Brochet F, and Dubourdieu D. 2001. The color of odors. *Brain Lang* 79:309-320. 10.1006/brln.2001.2493

518   Nehmé L, Barbar R, Maric Y, and Jacquot M. 2016. Influence of odor function and color symbolism in odor-color

519   associations: A French-Lebanese-Taiwanese cross-cultural study. *Food Quality and Preference* 49:33-41.

520   10.1016/j.foodqual.2015.11.002

521   Oleszkiewicz A, Resler K, Masala C, Landis BN, Hummel T, and Sorokowska A. 2023. Alterations of gustatory

522   sensitivity and taste liking in individuals with blindness or deafness. *Food Quality and Preference*

523   103:104712. 10.1016/j.foodqual.2022.104712

524   Olofsson JK, and Gottfried JA. 2015. The muted sense: neurocognitive limitations of olfactory language. *Trends Cogn*

525   *Sci* 19:314-321. 10.1016/j.tics.2015.04.007

526   Osterbauer RA, Matthews PM, Jenkinson M, Beckmann CF, Hansen PC, and Calvert GA. 2005. Color of scents:

527   chromatic stimuli modulate odor responses in the human brain. *J Neurophysiol* 93:3434-3441.

528   10.1152/jn.00555.2004

529   Robinson AK, Reinhard J, and Mattingley JB. 2015. Olfaction modulates early neural responses to matching visual
530   objects. *J Cogn Neurosci* 27:832-841. 10.1162/jocn_a_00732
531   Smeets MA, and Dijksterhuis GB. 2014. Smelly primes - when olfactory primes do or do not work. *Front Psychol*
532   5:96. 10.3389/fpsyg.2014.00096
533   Spence C. 2011. Crossmodal correspondences: A tutorial review. *Attention, Perception, & Psychophysics*
534   73:971-995. 10.3758/s13414-010-0073-7
535   Stevenson RJ, Boakes RA, and Wilson JP. 2000. Resistance to extinction of conditioned odor perceptions: evaluative
536   conditioning is not unique. *J Exp Psychol Learn Mem Cogn* 26:423-440. 10.1037//0278-7393.26.2.423
537   Stevenson RJ, Rich A, and Russell A. 2012. The nature and origin of cross-modal associations to odours. *Perception*
538   41:606-619. 10.1068/p7223
539   Tamura K, Hamakawa M, and Okamoto T. 2018. Olfactory modulation of colour working memory: How does citrus-
540   like smell influence the memory of orange colour? *PloS One* 13:e0203876. 10.1371/journal.pone.0203876
541   van Beilen M, Bult H, Renken R, Stieger M, Thumfart S, Cornelissen F, and Kooijman V. 2011. Effects of visual
542   priming on taste-odor interaction. *PloS One* 6:e23857. 10.1371/journal.pone.0023857
543   Zellner DA. 2013. Color–Odor Interactions: A Review and Model. *Chemosensory Perception* 6:155-169.
544   10.1007/s12078-013-9154-z
545   Zellner DA, McGarry A, Mattern-McClory R, and Abreu D. 2008. Masculinity/femininity of fine fragrances affects
546   color-odor correspondences: a case for cognitions influencing cross-modal correspondences. *Chem Senses*
547   33:211-222. 10.1093/chemse/bjm081
548   Zhang W, and Luck SJ. 2008. Discrete fixed-resolution representations in visual working memory. *Nature* 453:233-
549   235. 10.1038/nature06860

550

551

552   **Figure captions**

553   **Fig. 1 Experiment design and environment.** a) Experiment procedure; b) experiment

554   environment and a 20-mL vial containing 15 μl of the odorant solution; and c) procedure to

555   respond to the associated colors and descriptive ratings after sniffing an odorant; d) the circle in

556   the CIELa*b* color space to determine the color hue from cursor rotation. The labels around the

557   circle's perimeter indicate color names generally called.

558   First, the center rectangle's color hue was changed by rotating the cursor. The color hue was

559   determined by the cursor angle θ and the circle in the color space shown in d). Second, the lightness

560   was selected based on three steps. Third, after defining the associated color, the participants

561   provided descriptive ratings using the visual analog scale.

562

563   **Fig. 2 Color reproducibility between the different days in a) a*-axis, b) b*-axis, and c) L*-**

564   **axis values.** Gray bars indicated the 95% Bayesian confidence interval. Black circles indicate

565   estimated Bayesian mean values.

566

567   **Fig. 3 The mean and 95% confidence interval (CI) of the coefficients of *Edibility*, *Strength*,**

568   ***Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model**

569   **for the a*-value prediction**

570   The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars

571   indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars

572   indicate non-significant coefficients.

573

574   **Fig. 4 Plots of associated colors selected by each participant for significant odors in the**

575 **regression model for a* prediction**

576 (left) The selected colors are displayed along with the *Edibility* ratings. (middle) The colors are

577 modified to denote changes on the a*-axis in the CIEL*a*b* space. The a* values reflect the

578 individual responses of the associated colors. The colors of b* and L* values are fixed (L* = 70,

579 b* = 38; refer to Materials and Methods). The colors are reddish for higher a*-values. (right) The

580 a* values of the selected colors. The color bars indicate the range of a*- values.

581

582 **Fig. 5 The mean and 95% confidence interval (CI) of the coefficients of *Edibility*, *Strength*,**

583 ***Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model**

584 **for b*-value prediction**

585 The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars

586 indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars

587 indicate non-significant coefficients.

588

589 **Fig. 6 Plots of the associated colors selected by each participant for significant odors in the**

590 **regression model for b* prediction**

591 (left) The selected colors are displayed along with the *Edibility* ratings. (middle) The colors are

592 modified to denote changes on the b*-axis in the CIEL*a*b* space. The b* values reflect the

593 individual responses of associated colors. The colors of a* and L* values are fixed (L* = 70, a* =

594 20; refer to Materials and Methods). The colors are yellowish for higher b*-values. (right) The b*

595 values of the selected colors. The color bars indicate the range of b*- values.

596

597 **Fig. 7 Plots of the associated colors selected by each participant for significant odors in the**

598 **regression model for b* prediction**

599 (left) The selected colors are displayed along with the *Arousal* ratings. (middle) The colors are

600 modified to denote changes on the b*-axis in the CIEL*a*b* space. The b* values reflect the

601 individual responses of associated colors. The colors of a* and L* values are fixed (L* = 70, a* =

602 20; see Materials and Methods). The colors are yellowish for higher b*-values. (right) The b*

603 values of the selected colors. The color bars indicate the range of b*- values.

604

605 **Fig. 8 The mean and 95% confidence interval (CI) of the coefficients of *Strength*, *Edibility*,**

606 ***Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model**

607 **for L*-value prediction**

608 The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars

609 indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars

610 indicate non-significant coefficients.

611

612   **Fig. 9 Example plots of the associated colors selected for each odor by each participant**

613   (left) The selected colors are displayed along with the *Strength* ratings. (right) The L* values of

614   the selected colors. The color bars indicate the range of L*- values. The figure denotes two

615   examples of odors and the lightness of the associated colors; however, all odors indicate significant

616   effects on the *Strength* of the L* values (refer to Fig. 8).

617

618

The odorants and concentrations with solvents

1   **Table 1: The odorants and concentrations with solvents**

Odorants	Concentration [%]	Solvents
Trimethyl amine (30%)	0.025	Water
Butanoic acid	1.000	Water
4-ethyl-2-methoxyphenol	0.100	1,2-propanediol
2-ethyl pyrazine	0.400	Mineral oil
2,3-dimethylpyrazine	0.200	1,2-propanediol
Limonene	5.000	Mineral oil
Strawberry aldehyde (ethyl 3-methyl-3-phenylglycidate)	1.000	1,2-propanediol
4-methyl-3-penten-2-one	1.000	1,2-propanediol
Butyl acetate	1.000	1,2-propanediol
(1S)-(-)-α-Pinene	15.000	Mineral oil
Hydroxy citronellal	50.000	Mineral oil
Isovaleric acid	0.010	Mineral oil
Propane-1-thiol	0.001	1,2-propanediol

Pearson's correlation coefficients among the descriptive ratings

1 **Table 2: Pearson's correlation coefficients among the descriptive ratings**

	Strength	*Pleasantness*	*Familiarity*	*Edibility*	*Arousal*
Strength	-	-0.053	0.20	0.48	-0.0030
Pleasantness		-	0.45	0.12	0.45
Familiarity			-	0.21	0.50
Edibility				-	-0.087
Arousal					-

Figure 1

Experiment design and environment.

a) Experiment procedure; b) experiment environment and a 20-mL vial containing 15 μl of the odorant solution; and c) procedure to respond to the associated colors and descriptive ratings after sniffing an odorant; d) the circle in the CIEL*a*b* color space to determine the color hue from cursor rotation. The labels around the circle's perimeter indicate color names generally called.

First, the center rectangle's color hue was changed by rotating the cursor. The color hue was determined by the cursor angle θ and the circle in the color space shown in d). Second, the lightness was selected based on three steps. Third, after defining the associated color, the participants provided descriptive ratings using the visual analog scale.
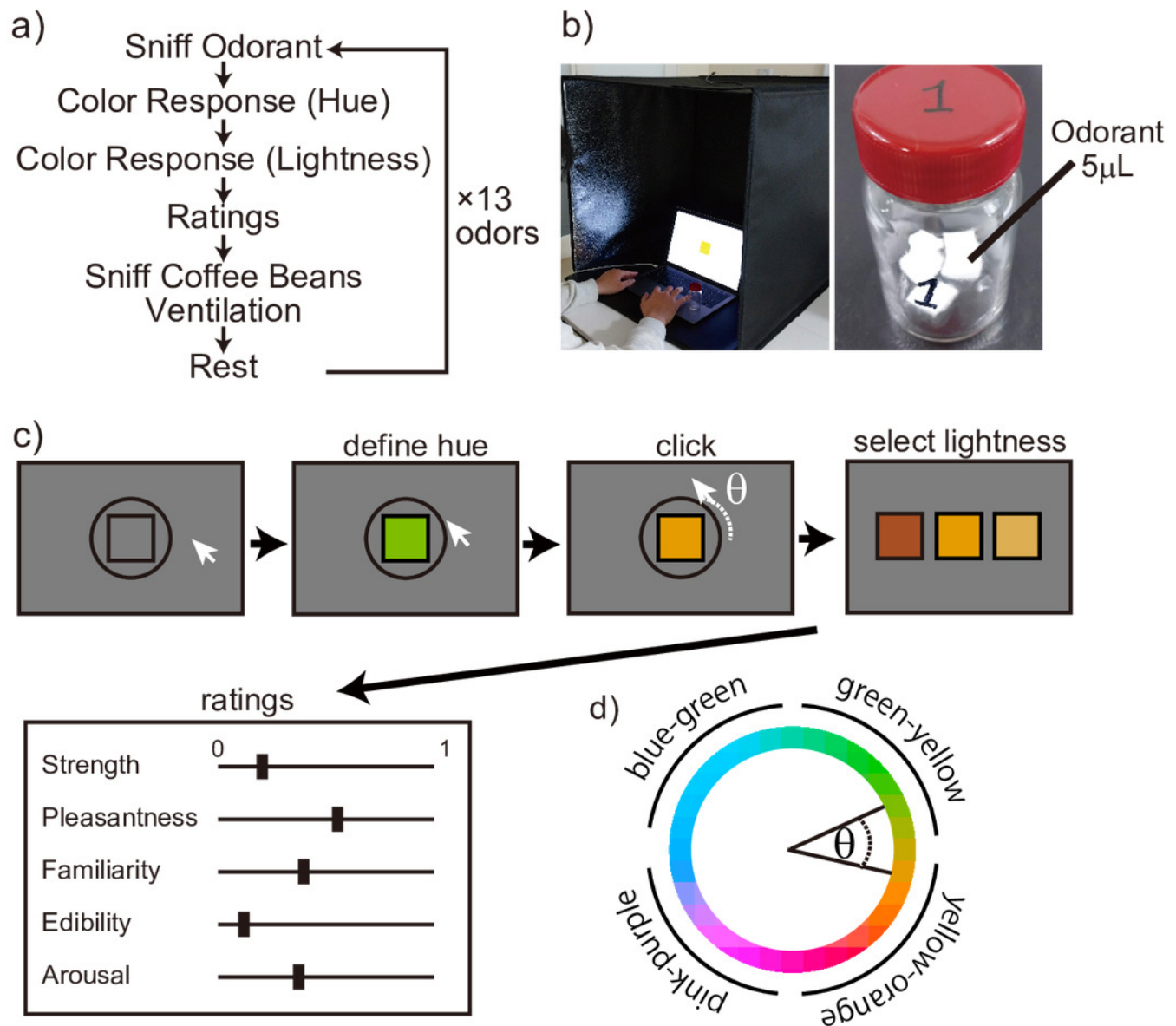
Figure 2

Color reproducibility between the different days in a) a*-axis, b) b*-axis, and c) L*-axis values.

Gray bars indicated the 95% Bayesian confidence interval. Black circles indicate estimated Bayesian mean values.
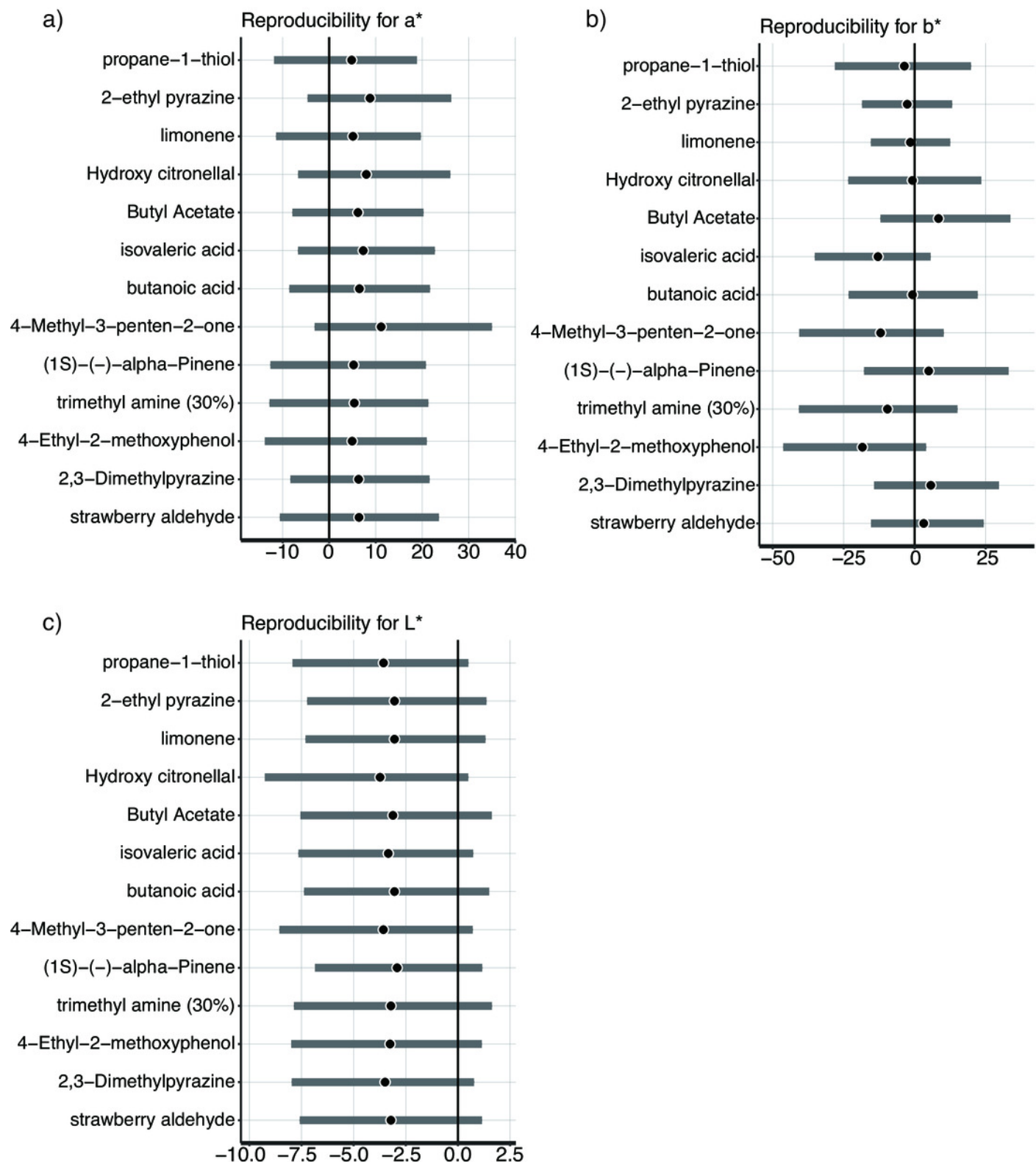
Figure 3

The mean and 95% confidence interval (CI) of the coefficients of *Edibility*, *Strength*, *Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model for the a*-value prediction

The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars indicate non-significant coefficients.
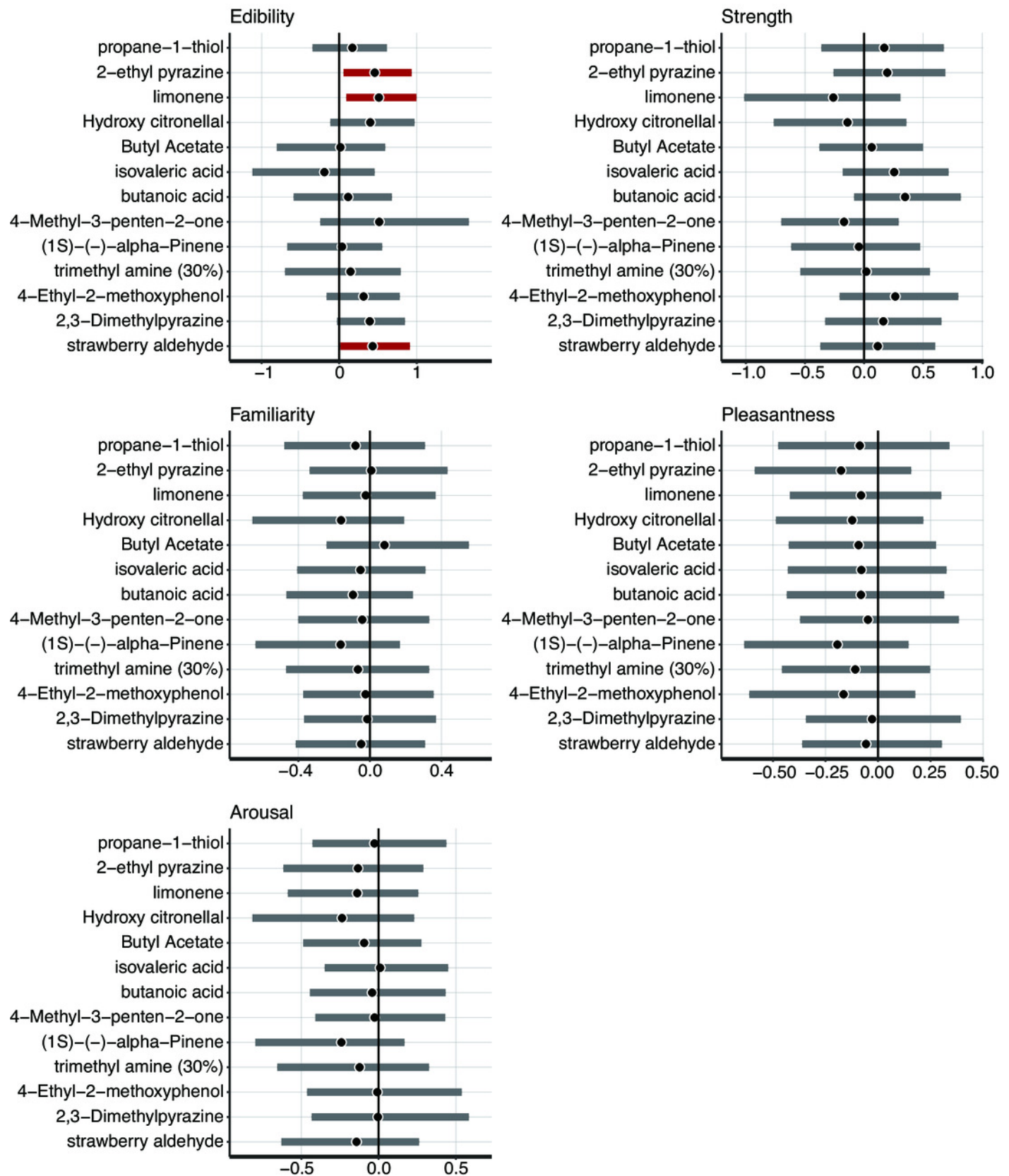
Figure 4

Plots of associated colors selected by each participant for significant odors in the regression model for a* prediction

(left) The selected colors are displayed along with the *Edibility* ratings. (middle) The colors are modified to denote changes on the a*-axis in the CIEL*a*b* space. The a* values reflect the individual responses of the associated colors. The colors of b* and L* values are fixed (L* = 70, b* = 38; refer to Materials and Methods). The colors are reddish for higher a*-values. (right) The a* values of the selected colors. The color bars indicate the range of a*- values.

2-ethyl pyrazine

Original Colors **Red-Green** **a* values**

limonene

Original Colors **Red-Green** **a* values**

strawberry aldehyde

Original Colors **Red-Green** **a* values**
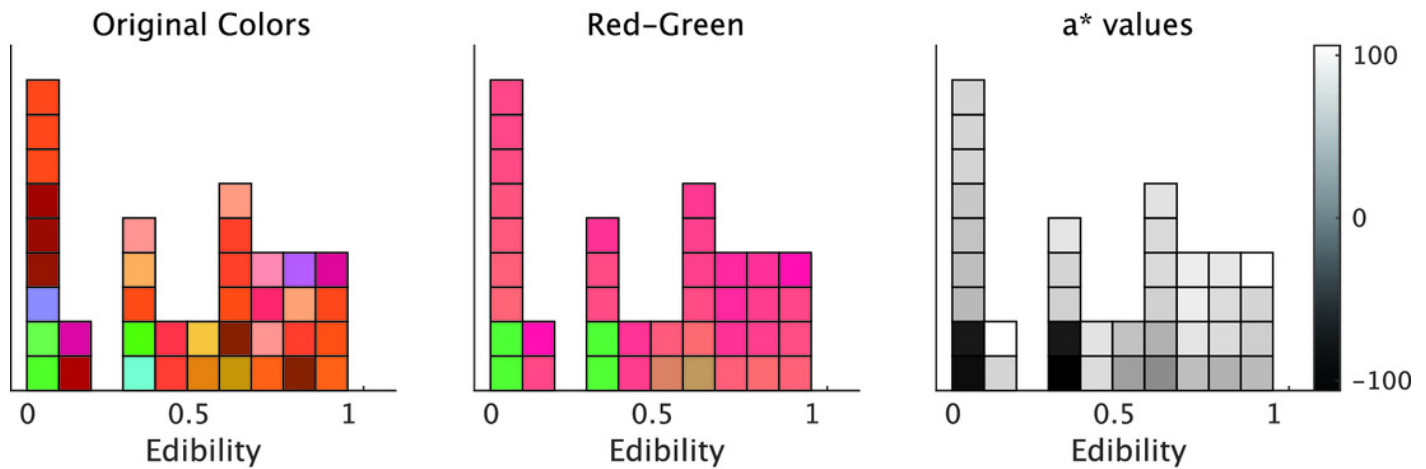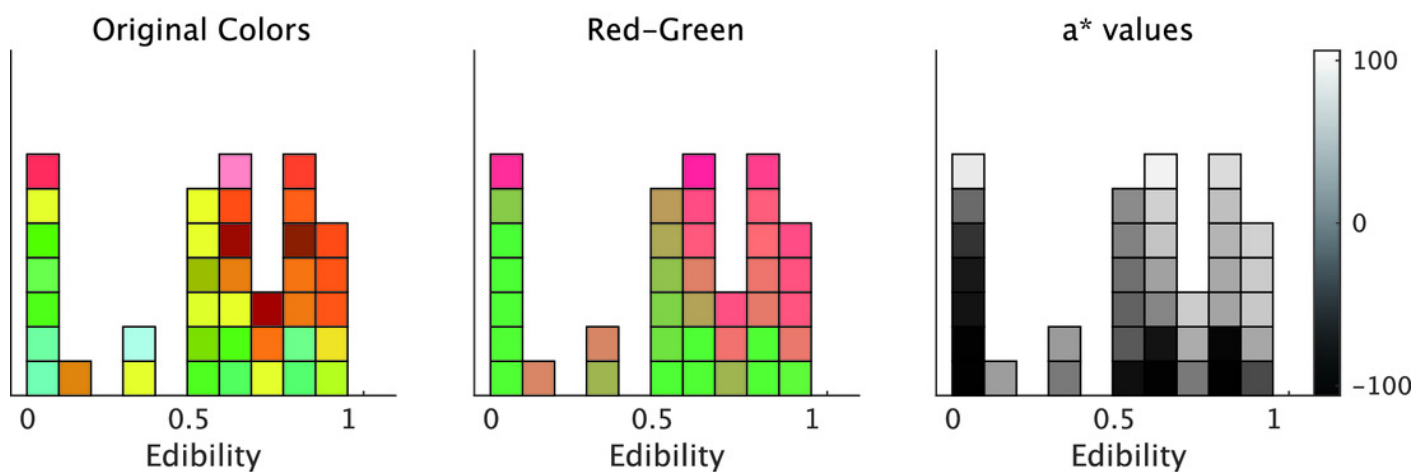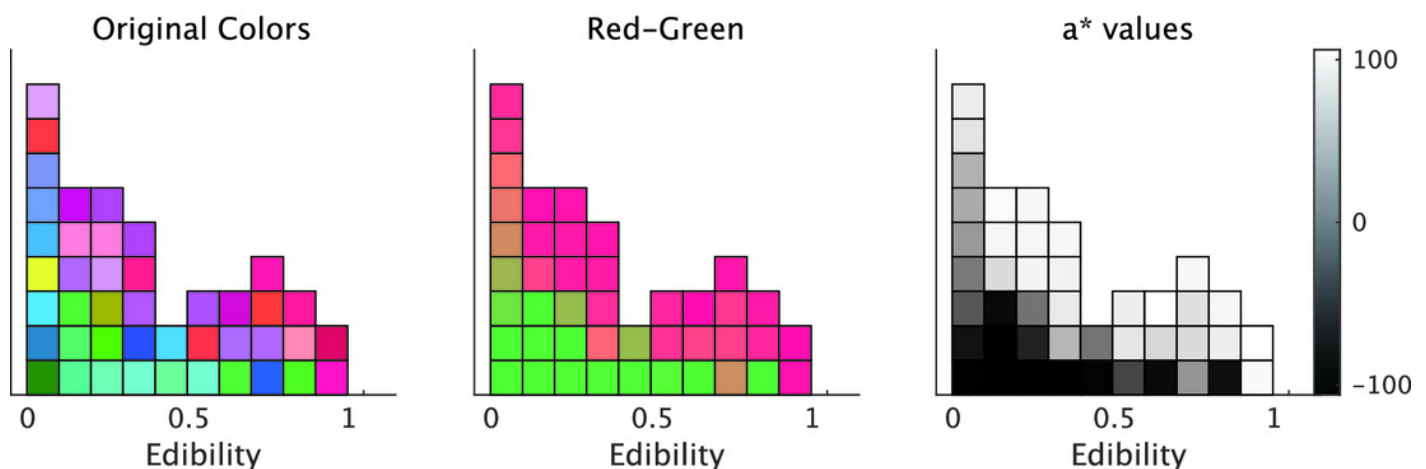
Figure 5

The mean and 95% confidence interval (CI) of the coefficients of *Edibility*, *Strength*, *Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model for b*-value prediction

The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars indicate non-significant coefficients.
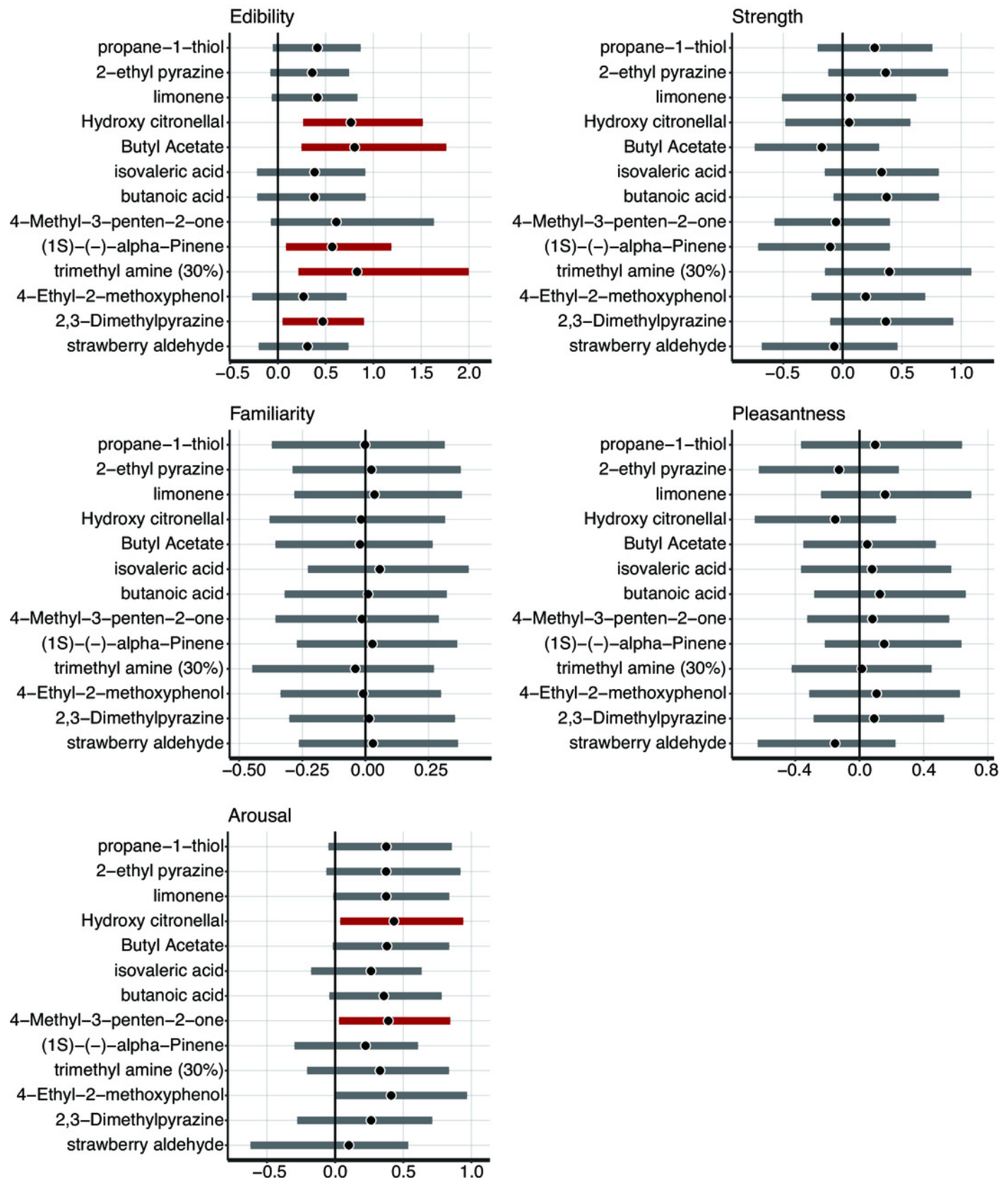
Figure 6

Plots of the associated colors selected by each participant for significant odors in the regression model for b* prediction

(left) The selected colors are displayed along with the *Edibility* ratings. (middle) The colors are modified to denote changes on the b*-axis in the CIEL*a*b* space. The b* values reflect the individual responses of associated colors. The colors of a* and L* values are fixed (L* = 70, a* = 20; refer to Materials and Methods). The colors are yellowish for higher b*-values. (right) The b* values of the selected colors. The color bars indicate the range of b*- values.

Hydroxy citronellal

Original Colors

Yellow–Blue

b* values

(1S)–(–)–α–Pinene

Original Colors

Yellow–Blue

b* values

2,3–Dimethylpyrazine

Original Colors

Yellow–Blue

b* values

Butyl Acetate

Original Colors

Yellow–Blue

b* values

trimethyl amine (30%)

Original Colors

Yellow–Blue

b* values
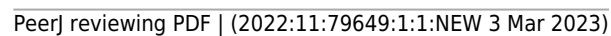
Figure 7

Plots of the associated colors selected by each participant for significant odors in the regression model for b* prediction

(left) The selected colors are displayed along with the *Arousal* ratings. (middle) The colors are modified to denote changes on the b*-axis in the CIEL*a*b* space. The b* values reflect the individual responses of associated colors. The colors of a* and L* values are fixed (L* = 70, a* = 20; see Materials and Methods). The colors are yellowish for higher b*-values. (right) The b* values of the selected colors. The color bars indicate the range of b*- values.
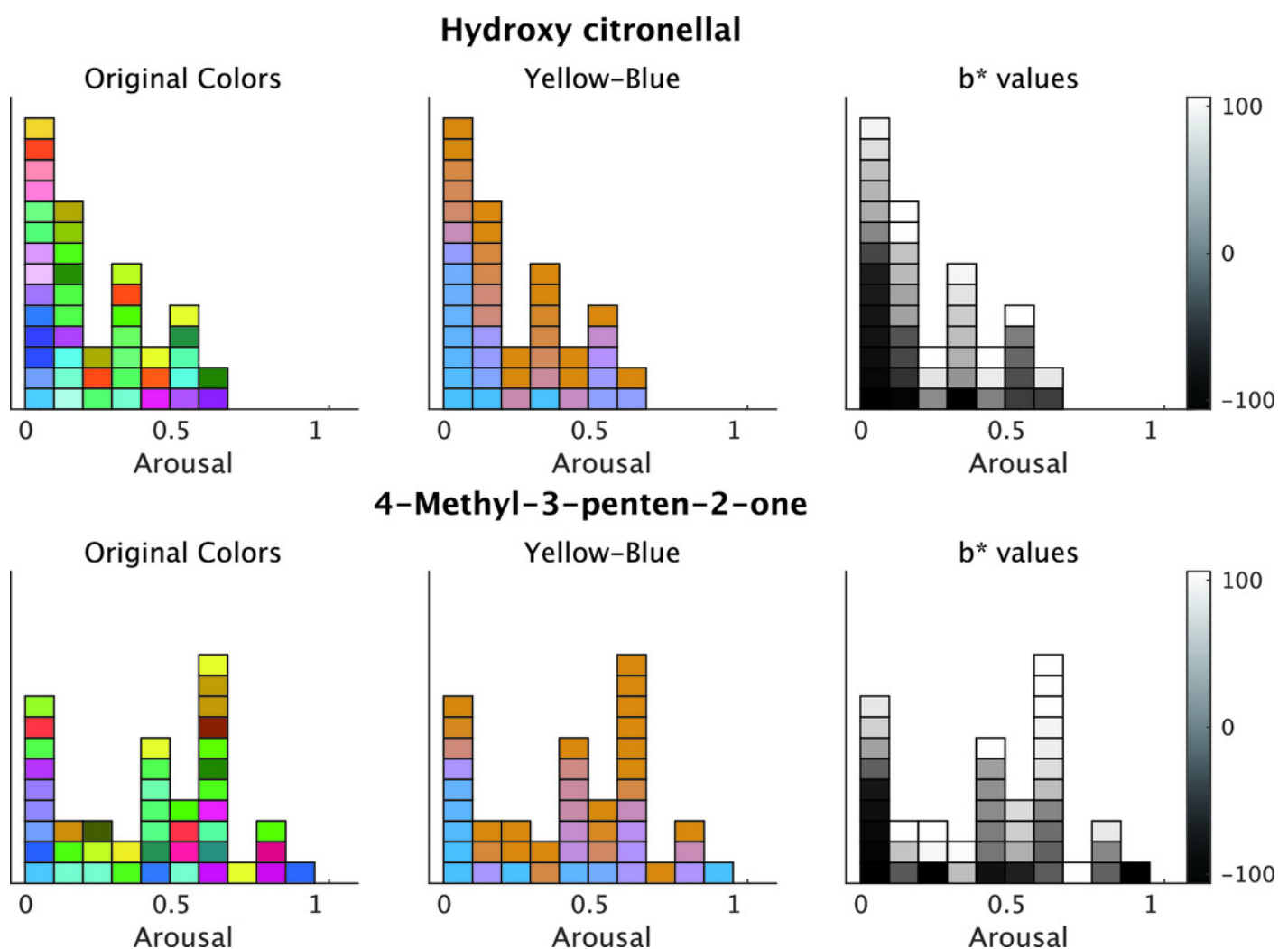
Figure 8

The mean and 95% confidence interval (CI) of the coefficients of *Strength*, *Edibility*, *Familiarity*, *Pleasantness*, and *Arousal* estimated by the Bayesian multilevel regression model for L*-value prediction

The black vertical line indicates 0. The black dots indicate the Bayesian mean, and bold bars indicate 95% Bayesian CI. The red bars indicate 95% significant coefficients, and the gray bars indicate non-significant coefficients.
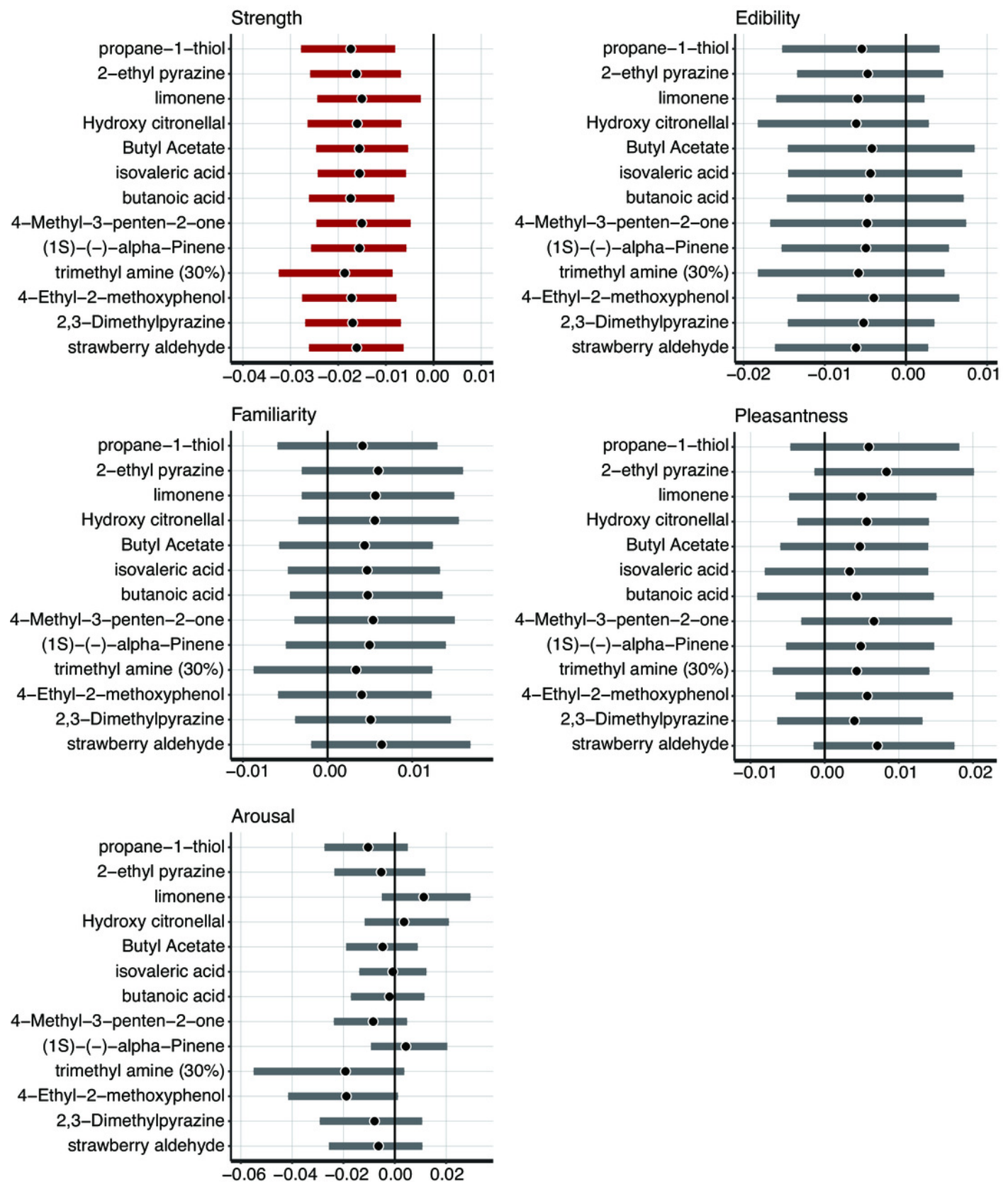
Figure 9

Example plots of the associated colors selected for each odor by each participant

(left) The selected colors are displayed along with the *Strength* ratings. (right) The L* values of the selected colors. The color bars indicate the range of L*- values. The figure denotes two examples of odors and the lightness of the associated colors; however, all odors indicate significant effects on the *Strength* of the L* values (refer to Fig. 8).

propane-1-thiol

4-Ethyl-2-methoxyphenol